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Computer Display Industry and Technology Profile

1.0 Introduction

Since World War II, cathode ray tube (CRT) electronic displays have played an increasingly important role in our lives, with televisions and personal computers being the primary applications. In the 1970's, the liquid crystal display (LCD) became popular in wristwatches and calculators. In the early 1980s, Epson introduced the first portable computer with a monochrome LCD display, followed soon by LCD monitor displays from Tandy and Toshiba. These electronic displays are commonly referred to as flat panel displays (FPDs).

There are now a number of flat panel displays (FPDs), each providing particular advantages for a given application. Appendix A[1] provides an overview of LCD and other FPD technologies. The LCD is by far the most common type of FPD, and currently is the only FPD used in commercial computer monitors, which includes laptop monitors. Computer monitors constituted approximately 54.7 percent of the $13.9 billion LCD market in 1997, and are predicted to increase to 67.4 percent of the $31.5 billion market in 2001.[2] LCDs comprised 87.6 percent of all FPD applications in 1997, and are expected to drop only slightly to 85.8 percent in 2003.[3] LCDs have greatly increased in number, type, and applications, including growth in the desktop monitor application. LCD desktop monitors, although not yet numerous in the commercial sector, appear to be a likely replacement technology for CRTs. Therefore, the potential for high market penetration and an increased LCD material volume is significant.

Concern over the environmental impact associated with the manufacture, use, and disposition of electronic products has emerged in recent years. These concerns have been driven in part because computer manufacturing requires the use of some toxic materials that may pose occupational and environmental risks. Concern has also been raised by the

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[1] Socolof, M.L., et al., *Environmental Life-Cycle Assessment of Desktop Computer Displays: Goal Definition and Scoping,* (Draft Final), University of Tennessee Center for Clean Products and Clean Technologies, July 24, 1998.

[2] Stanford Resources, presentation at the 1998 United States Display Consortium (USDC) Business Conference, San Jose, CA.

[3] Ibid.

growing numbers of consumer electronic products in the marketplace, creating an increasing volume of end-of-life (EOL) materials and some calls for changes in EOL management, especially in Europe. Producers, customers, legislators, regulators, and municipalities are interested in examining the resources used to produce and use these products, and in reducing environmental impacts throughout the entire computer product life cycle, especially during disposition at EOL.

In the consumer realm, CRT displays in televisions and computers dominate in terms of material volume, while LCDs found in household equipment (e.g., microwaves, stereos) and consumer items (e.g., watches, cell phones, pagers) dominate in terms of number of displays. Looking at all electronic displays in terms of material volume, it is helpful to analyze three categories separately. The largest displays (>40-inches) are generally in projection format, and thus consume relatively small material volumes; they are also produced in relatively small unit volumes. The smallest displays (<5-inches) are produced in large volumes (over 1.6 billion units in 1998), but tend to be part of larger systems (appliances, stereos) and so are a relatively small part of the overall material volume. It is in the middle sizes (5- to 40-inches) that the display material volume is a large fraction of the system, and unit volumes are significant.

In order to assess environmental impacts of both CRTs and LCDs during manufacturing, use, and disposition stages, the United States Environmental Protection Agency Design for the Environment (DfE) Program formed a voluntary partnership with the display industry. The goal of the DfE Computer Display Project is to study the life cycle environmental impacts of CRT and LCD desktop computer displays, and generate data that will assist the display industry to make environmentally informed decisions and identify areas for improvement. The selection of these two types of displays was based on potential end-of-life material volume, widespread use, and the ability to compare two display types with the same functional unit—desktop computer application.

The purpose of the Computer Display Industry and Technology Profile is to provide an overview of the CRT and LCD computer monitor markets and technologies. Section 2.0 presents a market profile based on currently available data. The profile is not an exhaustive market assessment, and does not intend to imply preference to one technology type. Section 3.0, Technology Profile, presents an explanation of the basic operation and manufacturing of CRTs and thin-film transistor (TFT) -LCDs to readers relatively unfamiliar with the topic.

2.0 Industry Market Profile

2.1 Computer Monitors: Volume and Technology Trends

Virtually a one-to-one ratio exists between the number of computers and the number of displays in the marketplace. Because the world market for computers has grown so rapidly, a corresponding increase in displays can also be expected. Sales of personal computers (PCs) are expected to continue to grow beyond the year 2000. Many PCs will be desktop systems. ADI Corporation estimated worldwide demand for PCs at 66 million units in 1996, growing to 86.63 million in 1998, and over 100 million in 2000.[4] Desktop applications make up most of these sales.

The United States has been a major market for computers. The U.S. Bureau of the Census estimates that in 1993, 43.2 percent of the U.S. working population used a computer at work, compared with 34.8 percent in 1989 and 23.2 percent in 1984. Also in 1993, 22,605,000 households owned a home computer, up from 13,683,000 in 1989, and 6,980,000 in 1984.[5]

2.1.1 CRTs

The computer monitor has been one of the two largest applications for CRTs; the other has been television. According to a report published by Fuji Chimera Research, the 1995 worldwide market for monitor CRTs was 57.8 million units, 28 million of which (48.5 percent) were consumed in North America.[6] According to the same source, 1996 worldwide CRT monitor demand increased to 67.1 million units.[7] Stanford Resources reports that the CRT monitor market reached 84.2 million units in 1997 (25.6 million in the United States), and anticipates a worldwide growth to more than 100 million units in 2002, reaching 113.5 million in 2003.[8]

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4 *Nikkei Microdevices' Flat Panel Display 1997 Yearbook*, Nikkei Business Publications, Inc., p. 98.

5 "Computer Use in the United States: October 1993," U.S. Bureau of the Census, Current Population Reports, Special Series P-23.

6 *The Future of Liquid Crystal and Related Display Materials*, Fuji Chimera Research, 1997, p.12.

7 Ibid.

8 Stanford Resources, Inc., web site.

In order to keep pace with more demanding computer applications, CRTs have been continually improved: larger screen sizes, higher resolution (for Windows, Macintosh OS, and Web-page font challenges), and higher luminance (for videos). This improvement is likely to continue, as the market moves away from sales of smaller (14-inch and 15-inch) monitors, toward 19-inch and 21-inch monitors. Features that were once accompanied by a high price tag are becoming more standard. Reduced dot pitch; color matching; flatter, lighter weight, touch-sensitive screens; and digital cameras are some of the new offerings at lower prices. This is due, in part, to an increased number of CRT suppliers in the marketplace and improvements in technologies, such as aperture grille, Invar shadow mask, and the flatter Trinitron CRT.

The marketplace is seeing other changes in CRTs, such as shorter necks that reduce the depth by at least three inches on a 17-inch monitor. DisplaySearch reports that while a wider deflection yoke angle enables this development, it causes problems with focusing, which may require more circuitry to resolve. A number of companies have recently released new monitors, many in the 17-inch and 19-inch range.

2.1.2 LCDs

Although market analysts predict growth in the CRT monitor market through the first few years of the 21st century, it is widely anticipated that after that point, LCDs will begin to erode the CRT stronghold. Although the portable computer is currently the major application for LCDs, industry analysts expect this technology to increasingly penetrate the desktop monitor market, particularly in the 15-inch to 20-inch range. Industry experts anticipate that by 2000, LCDs will have captured 5.4 percent of the monitor market. The United States is a primary market for LCD monitors, and will grow into an even stronger market by the end of the century. NEC estimates that the United States will receive over half of the forecasted 6.4 million LCD monitors shipped in 2001 (see Figure 2-1). DisplaySearch also forecasts that the United States will constitute 30 percent of the worldwide LCD monitor market in 2001, with total LCD monitor sales of 7.7 million units. DisplaySearch predicts a worldwide LCD monitor market of $4.2 billion by 2000.[9]

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[9] *DisplaySearch Monitor*, April 1997.

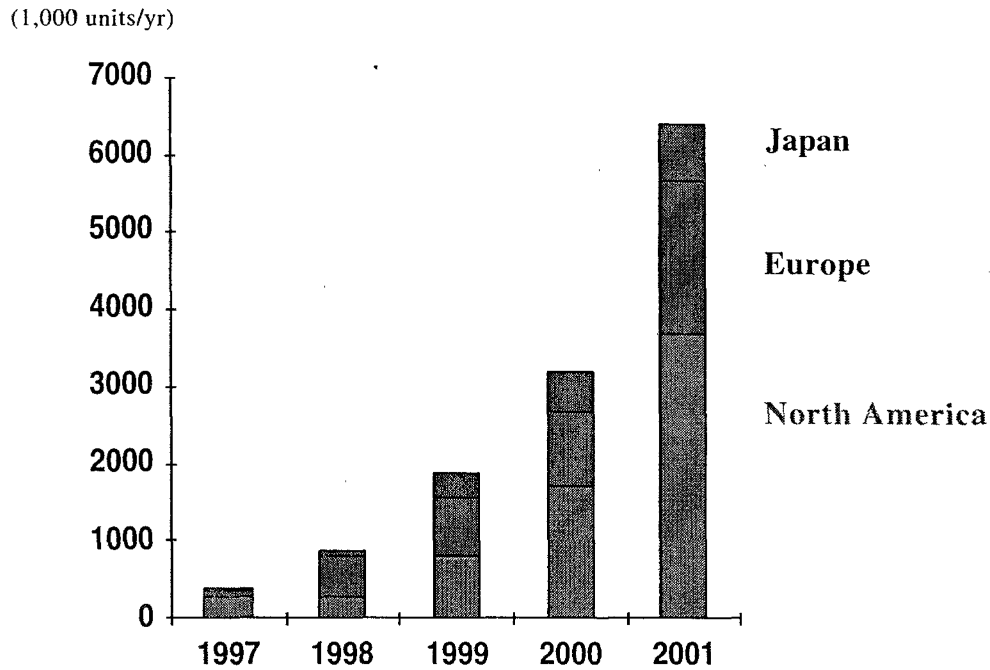

Figure 2-1: LCD Monitor Forecast[10]

LCD monitors are primarily active-matrix LCD (AMLCD), most of which are thin-film transistor (TFT) structures. Super-twisted nematic (STN), a passive-matrix LCD (PMLCD) technology, competes in some areas with AMLCD. Although some monitors are based on an STN structure, STN-LCDs are primarily found in electronic organizers and measurement devices. While STN-LCDs offer a cost advantage over TFT-LCDs, prices for the latter technology have been dropping. DisplaySearch reports that the TFT market will grow from $4.87 billion in 1996 to $13.7 billion in 2000, whereas the STN market is expected to drop slightly from $4.3 billion to $4.2 billion during the same time period.[11]

At Computex Taipei '97, a leading computer exhibition, over 20 companies displayed more than 100 models of LCD monitors.[12] A number of companies promoted both AMLCD and PMLCD monitors. More recently, DisplaySearch reported that over 180 LCD monitors are marketed by 50-some companies, 81 percent of which use thin-film TFT-LCD technology,

[10] *Nikkei Microdevices' Flat Panel Display 1998 Yearbook*, Nikkei Business Publications, Inc., p. 80.
[11] *DisplaySearch Monitor*, April 1997.
[12] *Information Display*, Official Publication of the Society for Information Display, October 1997, p. 37.

and 19 percent of which use STN technology.[13] According to DisplaySearch, TFT-LCD monitor shipments will grow from 1.1 million in 1998 to 13.1 million in 2002.[14] Between 1998 and 2001, the 15-inch display is expected to make up the greatest share of these monitors.[15]

Currently, the greatest obstacle facing LCDs in the desktop monitor market is not competition from other LCD technologies, but a high price tag relative to that of CRTs. TFT-LCD monitors currently cost several times that of a CRT monitor, with a 15-inch unit costing $1200. There are indications that the price of TFT-LCDs will continue to decrease, prices have already dropped to $900. Most of the LCD monitor sales have been to the medical and financial community, but expectations are that the customer base will spread when a 3:1 cost ratio with CRTs is reached, and even more so as prices continue to decline. Surveys indicate that given a 1.5:1 cost ratio of FPDs to CRTs, 30 percent of consumers would opt for the FPD. DisplaySearch reports that low prices by Korean LCD suppliers will likely bring prices of 15- and 18-inch LCD monitors down to a 2X price ratio with 17" and 19" CRTs by the end of 1998.

2.2 Manufacturing Locations and Suppliers

2.2.1 CRTs

The majority of CRT display fabrication takes place outside of the United States. In 1997, Asia (excluding Japan) produced 54 percent of all color TVs and 79 percent of all CRT monitors.[16] DisplaySearch reports that Japan supplies between 10 and 15 percent of CRTs produced worldwide, primarily 17-inch and larger. The greatest concentration of CRT manufacturers is in Taiwan, where 33.6 percent of total world production took place in 1996.[17] South Korea and China are also becoming major sites for CRT monitor production. Most color CRT monitors and small TV CRTs (less than 19 inches) are produced outside the United States. Due to the cost of transporting heavier displays, some TV CRTs, 19 inches and larger, are produced in the United States. It is possible that a

[13] Presentation by DisplaySearch at the USDC Business Conference: *Enabling New Display Markets*, Display Works, January 20, 1998, San Jose, CA.

[14] DisplaySearch FPD Equipment and Materials Analysis and Forecast, Austin, Texas, June 1998.

[15] Ibid.

[16] *The Future of Liquid Crystal and Related Display Materials*, Fuji Chimera Research, 1997, p. 12.

[17] *Stanford Resources, Inc.*, web site.

similar situation will arise with larger CRTs monitors.[18] See Table 2-1 for regional production figures for CRT monitors.

	1994	1995	1996	1997	1998	2000
Europe	3,500	3,850	4,300	4,800	5,300	6,000
North America	800	1,000	1,200	1,500	1,800	2,400
Asia	41,000	45,650	53,000	60,000	65,000	75,000
Japan	5,300	6,080	7,100	8,000	9,000	10,000
So-Central America	800	1,200	1,500	1,900	2,500	3,200
Total	51,400	57,780	67,100	76,200	83,600	96,600

Table 2-1: Color CRT Monitors Production by Region (,000 units)[19]

As is the case with most commodity goods, CRT monitors are distributed by the manufacturer via different routes. They may be sold under the manufacturer's name through retail channels, or to original equipment manufacturers (OEMs) or other system retailers, such as Dell Computers. Major manufacturers and retailers include Acer, Apple, Compaq, CTX, Dell, Digital, Eizo, Hitachi, Hewlett Packard, IBM, Iiyama, LG, MAG, Mitsubishi, NEC, Nokia, Panasonic, Samsung, Sharp, Siemens Nixdorf, Sony, Toshiba, and Viewsonic.

Figure 2-2 shows the 1997 market share in the United States per CRT monitor brand name. In this table, some manufacturers (such as Sony) will be under-represented, as the monitors they manufacture for other companies may carry the brand name of the other company (e.g., Sony monitors manufactured for Dell). Figure 2-3 provides data on the 1996 industry market share for main color CRT monitor-tube manufacturers.

[18] Reported at the Glass Roundtable meeting, February 6, 1997, University of Texas at Austin.

[19] *The Future of Liquid Crystal and Related Display Materials*, Fuji Chimera Research, 1997.

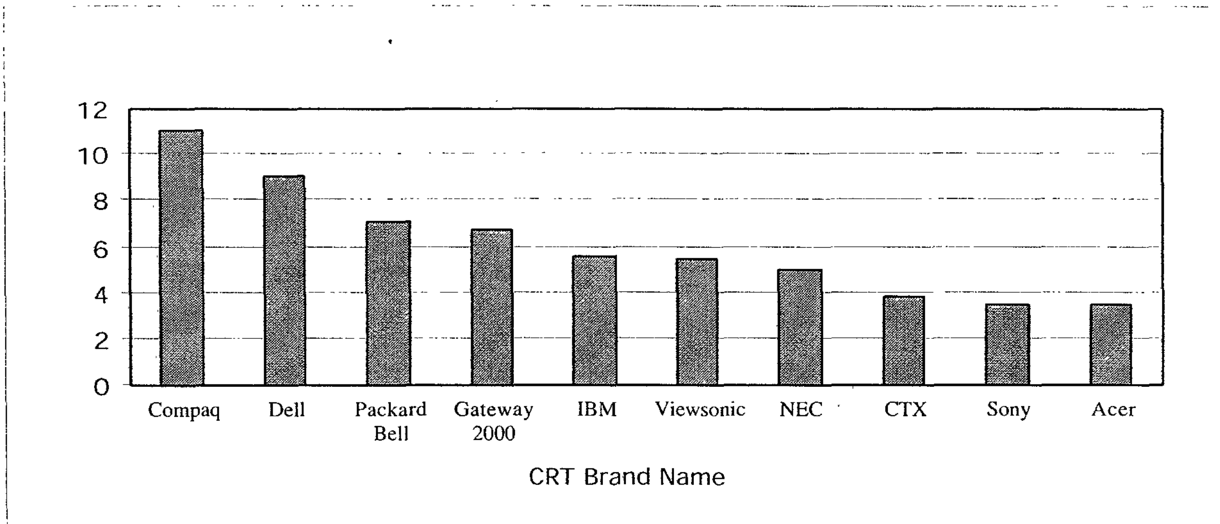

Figure 2-2: CRT U.S. Market Share (Percent) by Brand Name[20]

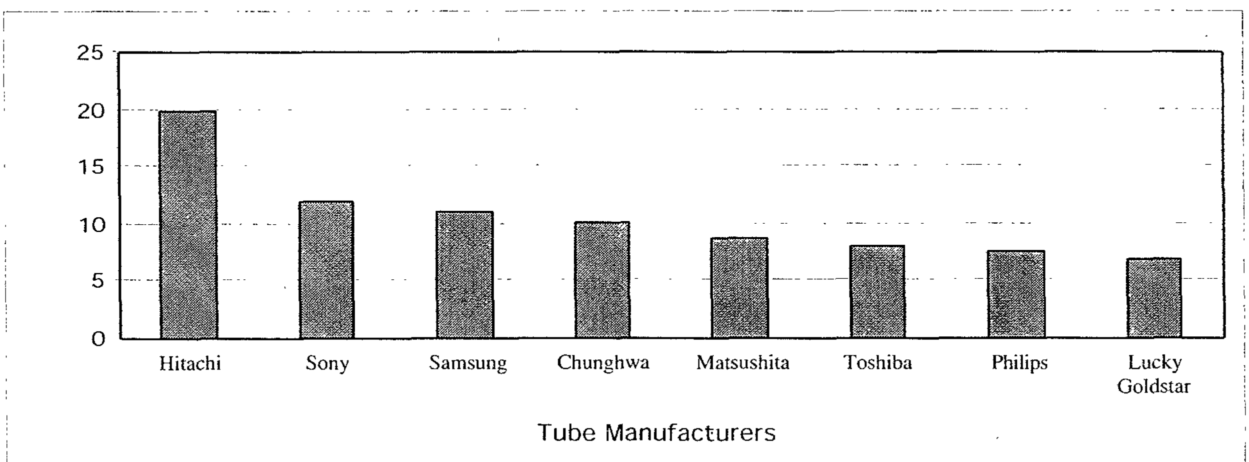

Figure 2-3: Worldwide Market Share (Percent) of Color CRT Tube Manufacturers[21]

20 Source: Stanford Resources, 1997 data.

21 Source: Stanford Resources, 1996 data.

2.2.2 CRT materials and subassemblies

The majority of CRTs (TVs and monitors) and CRT-related components and materials are manufactured outside of the United States. The major materials, components and subassemblies are as follows:

- Faceplate
- Funnel
- Neck
- Phosphors
- Frit
- Aquadag
- Lacquer coating
- Shadow mask assembly
- Electron gun assembly
- Deflection yoke
- Deflection amps
- Centering magnets
- Printed wiring boards (PWBs)
- Anti-static/anti-glare coating

For a more extensive listing, see the CRT process flow and bill of materials in Appendices A and B, respectively .

There are approximately 100 CRT manufacturers worldwide.[22] In the United States, there are five CRT glass manufacturing plants, producing approximately 600K tons of product annually: Thomson, Techneglas (two sites), and Corning (three sites, with one being a joint venture with Sony). Glass is imported from Asahi, NEC, Samsung, Schott, and Philips.

Sony is the only manufacturer of color monitor tubes in the United States, although they, along with Hitachi, Matsushita, Philips, Thomson, Toshiba, and Zenith, do produce TV-tubes in the United States. Aydin, Compaq, Display Tech, Digital Equipment Corporation, IBM, Modicon, NCR, and Unysis assemble computer displays domestically.

Techneglas, in addition to being a major North American manufacturer of panel and funnel glass, is a large producer of frit, planar dopants, and glass resins. Phosphors are supplied internally from vertically integrated manufacturing facilities and by foreign manufacturers (primarily in Japan).

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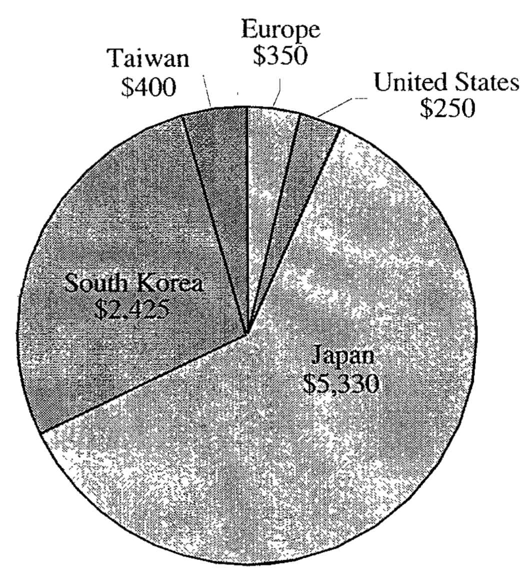
22 *Electronic Engineering Times*, December 1, 1997, num. 983, p. 27.

The remainder of the components and subassemblies are produced primarily in Asia. Although shadow masks for TVs are produced in United States, no United States manufacturer has established a high-volume, high-resolution shadow mask facility for monitors. Nippon Printing and Dai Nippon Screening are primary producers in Asia. Electron guns are made from precision metals parts, a significant portion being manufactured by Premium Allied Tube. Insulator glass used in the gun assembly is supplied by Corning Asahi Video and Techneglas. Deflection yokes and amps are produced primarily in the United States, Canada, and Taiwan, and there are a couple of domestic producers of centering magnets.

2.2.3 LCDs

The number of LCD suppliers is significantly lower than the number of CRT suppliers, primarily due to the high capital cost of manufacturing FPDs. As shown in Figure 2-4, Japan leads in AMLCD investment, followed by South Korea. More recent data from DisplaySearch shows that LCD capital investment by Japanese and Korean companies will decrease significantly in 1998 to $676 million, down from $3.85 billion the previous year.



Source: POSTECH

Figure 2-4: Capital Investment in AMLCD Production 1994-1996 ($millions)

In 1995, Japan manufactured 94.7 percent of all LCDs, followed by Korea at 3.5 percent and Taiwan at 1.7 percent; 0.1 percent were produced outside of these regions. By 2005, Japan is forecasted to lead LCD production, with 75 percent. Korea is expected to increase its share to 12.9 percent, and Taiwan to 11.9 percent; 0.2 percent will be produced elsewhere.

Korean and Taiwanese LCD manufacturers have been able to enter this market partially due to strategic relationships with Japanese companies. Samsung Electronics has established technical cooperation with Fujitsu for TFT-LCDs. LG (Lucky Goldstar) Electronics jointly developed technology with Alps Electric. CPT is in technical cooperation with Mitsubishi for TFT-LCDs. Chunghwa Picture Tubes has a partnership with Toshiba for STN-LCDs and is searching for a partner in TFT development. In addition, IBM and Acer are working together on TFTs, as are Toshiba and Walsin Linwa.

2.2.4 LCD materials and subassemblies

The LCD manufacturing process, particularly for TFT-LCD, is more complex in terms of types of materials and process steps than is the CRT process. The following list has been abbreviated to provide only the major materials, components, and subassemblies. For a more complete listing, refer to Appendices C and D for the TFT-LCD process flow and bill of materials, respectively.

- Front glass panel
- Color filter materials
- Indium tin oxide
- Back glass panel
- Liquid crystal materials
- Transistor metals
- Alignment material
- Etchants
- Photoresists
- Developing solution
- Sealer
- Spacers
- Polarizing material
- Driver ICs
- Backlight units
- PWB

Almost all of the materials, components, and subassemblies for LCD monitors are made in Asia. The exceptions are backlights and some driver integrated circuit (IC) devices, which are produced in North America or Europe.

3.0 Technology Profile

3.1 CRT Operation and Components

The cathode ray tube (CRT), whose basic components are shown in Figure 3-1, uses high voltages to move electrons toward a display screen. The electrons are emitted from a cathode and concentrated into a beam with focusing grids. The beam is accelerated toward the screen, which acts as an anode, due to a conductive coating. The screen is also coated with a luminescent material (a phosphor), typically zinc sulfide. This phosphor converts electromagnetic radiation (the kinetic energy of the electrons) into light—a phenomenon called phosphorescence.[23] The *cathode ray* is essentially an electric discharge— the stream of electrons— in a vacuum tube.

The beam passes through either horizontal and vertical deflection plates (mutually perpendicular pairs of electrodes) or magnetic deflecting coils in the deflection yoke. Voltage is applied to these plates (or coils) to control the position of the beam and its line-by-line scanning across the screen.

Video signal (information to be displayed on the screen) is applied to the electrode (cathode) and is contained in the electron beam. This video signal, which controls the current to the electron-beam, is applied in synchronization with the deflection signals. The result is two-dimensional information displayed on the screen.

[23] The materials that phosphoresce are referred to as phosphors. Phosphors do not contain phosphorous.

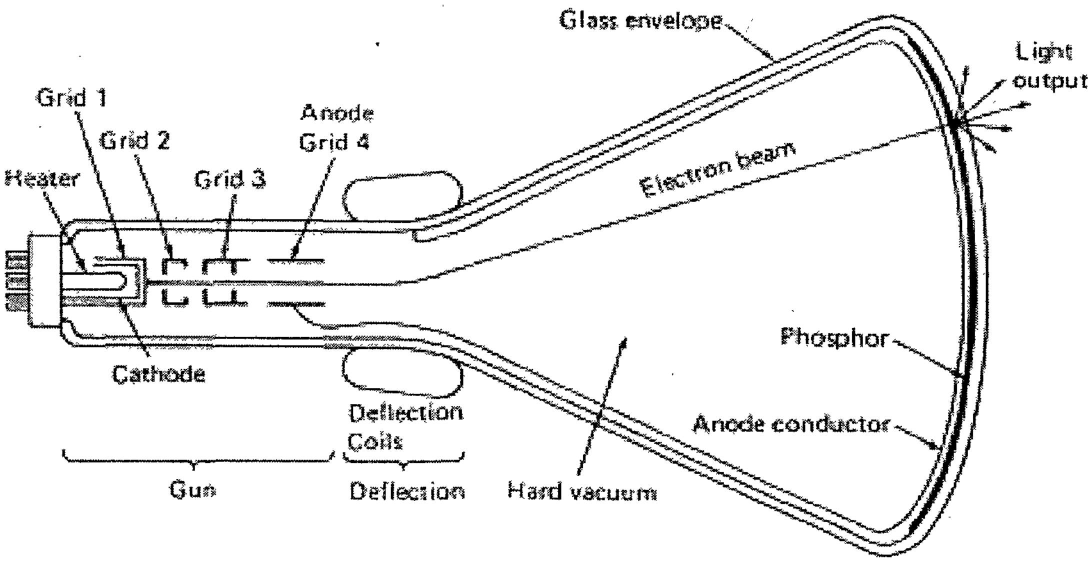


Figure 3-1: Cathode Ray Tube Fundamentals

Color images are made possible through several techniques. The most common technique is the use of a shadow mask, widely used in consumer TVs and monitors (see Figure 3-2). This technique requires three electron guns, which emit electrons that then pass through an aperture—a shadow mask—before hitting the screen. Different phosphorescing colors are obtained by adding materials to the zinc sulfide coating on the screen. The beam impacts the screen at precise locations, striking only one of three colored regions: a red, green, or blue area, and emits visible light. When this point source of light strikes the corresponding dot, a shadow of the mask falls on the inside of the screen. The three beams are controlled (deflected) by one yoke, enabling the three beams to strike the corresponding dots simultaneously, and requiring only one focus control.

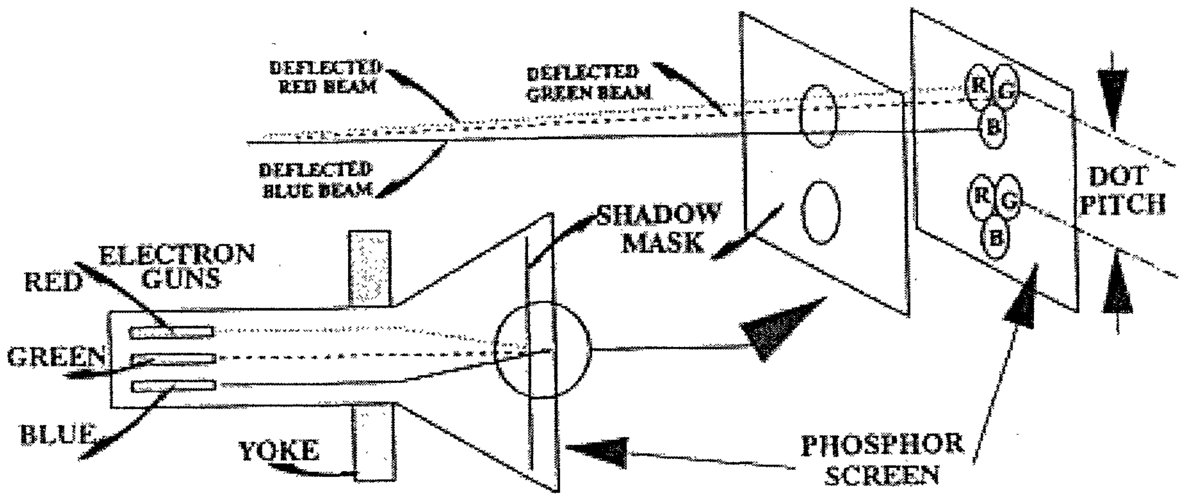


Figure 3-2: Shadow Mask Color CRT[24]

The most common alternative to the shadow-mask technique is the Trinitron, which uses an aperture grill (rather than a shadow mask) that is composed of parallel, colored stripes, (rather than dots). A grid positioned in front of the stripes directs the beam to the appropriate color. Although the Trinitron design offers certain performance and warrants investigation, the scope of this operational and manufacturing description is limited to the shadow mask structure.

3.2 CRT Manufacturing Process[25]

The traditional CRT glass manufacturing process is comprised of the following main categories of activities:

- Glass fabrication
- Faceplate (screen) preparation
- Shadow mask fabrication/assembly
- Funnel preparation

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[24] Castellano, J.A.,*Handbook of Display Technology*, Academic Press, Inc., 1992, pg. 42,

[25] *Environmental Consciousness: A Strategic Competitiveness Issue for the Electronics and Computer Industry*, MCC, 1993.

- Bulb joining
- Electron gun fabrication
- Final assembly

3.2.1 CRT glass fabrication

Raw materials are converted to a homogeneous melt at high temperatures and then formed into the glass panel (see Figure 3-3). Sand is the most common ingredient and must be chosen according to high quality, high purity, and grain-size standards. The sand and soda ash can be sourced within the western United States, whereas limestone may come from the coast of the Bahamas. Other raw materials such as boron (used as anhydrous borax or boric acid) come from California or Turkey.

Dry blending mixes the raw materials, and small amounts of liquid may be added for wet blending. The batch is then preheated to temperatures approaching that of the furnace and charged into the furnace, where melting and other reactions (dissolution, volatilization, and redox) take place. The next phase, fining, removes bubbles chemically and physically from the molten glass melt. The most commonly used fining agents are sulfates, sodium or potassium nitrates, and arsenic or antimony trioxides. The melt is then conditioned, or homogenized, and then cooled prior to fabrication. After forming, the glass must be prepared to withstand upcoming chemical, thermal, and physical activities and to meet high quality standards for optical glass. These activities include some, or all, of the following: beveling, chamfering, grinding, polishing, and annealing at 350-450 degrees Celsius. In some cases, breakage occurs during the manufacturing process, in which case the broken glass—*cullet*—can be reintroduced into the batch melt.

3.2.2 Faceplate preparation (pattern)

The CRT faceplate, also referred to as a panel or screen, is coated with a conductive material and a luminescent material (the phosphors). The conductive coating, an aquadag, acts as an anode, attracting the electrons emitted from the electron guns. The coating is composed of electrically conductive carbon particles, with silicate binders suspended in water. It is deposited by painting, sponging, spinning, or spraying, and then baked to increase durability.

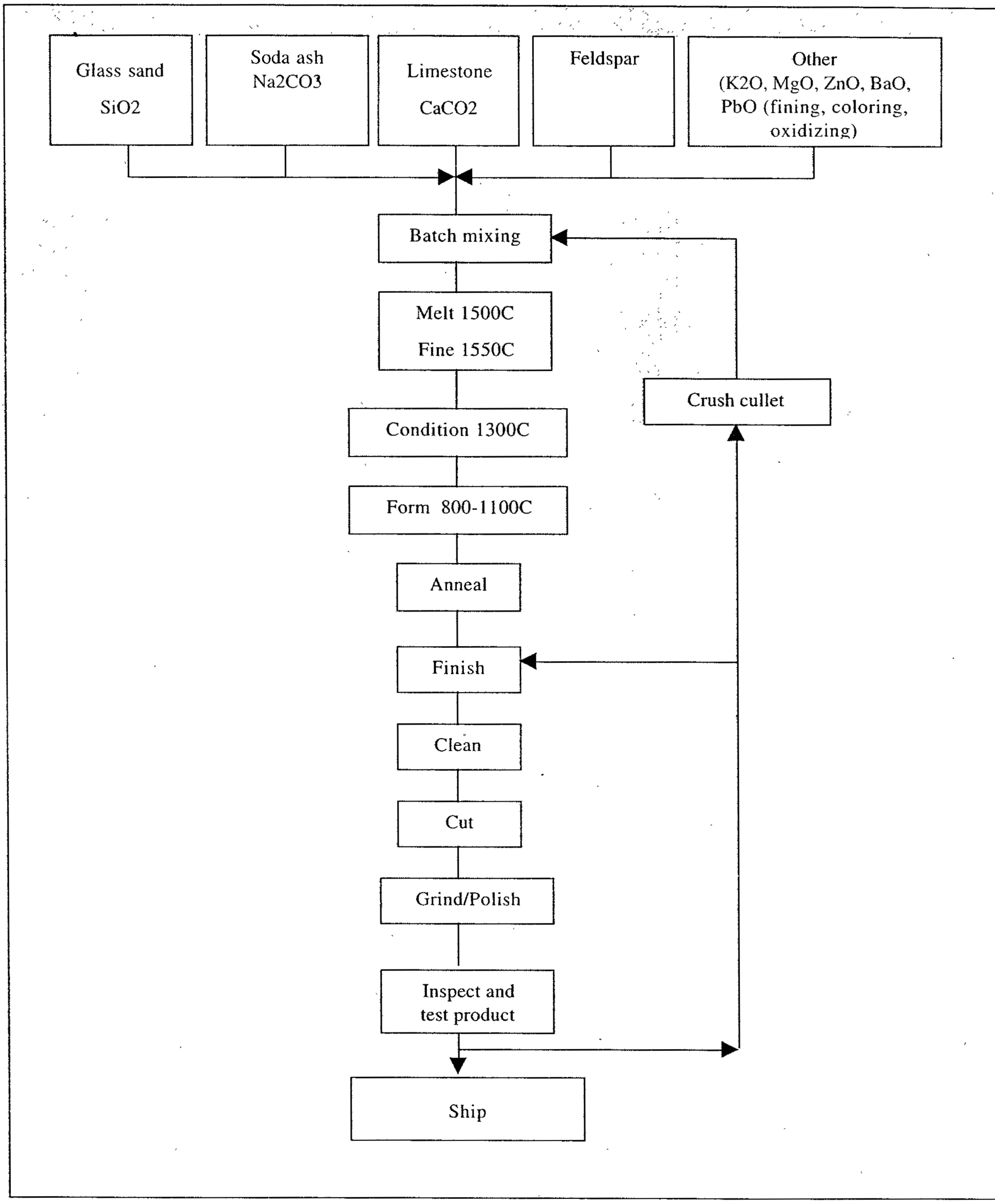

Figure 3-3: Glass Manufacturing Process Flow[26]

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26 Encyclopedia of Chemical Technology, 3rd Edition, vol 11, 1980, p. 847.

The luminescent phosphor and contrast-enhancing materials are applied to the inside surface of the faceplate in aqueous solutions, using spin coaters. These coatings are patterned by photolithography, using polyvinyl alcohol (PVA) photoresists and near-ultra-violet exposure lamps. Exposure of the photoresist material from light passing through the apertures in the shadow mask creates a pattern of dots (or stripes) where the red, green, and blue phosphors will be placed in subsequent steps. These phosphor materials are powders that are applied one at a time in dichromate-sensitized PVA slurries (a thin paste that has solids suspended in liquids).

The pattern is developed by rinsing with a solvent to wash away the unexposed resist. Next, a coating of contrast-enhancing material (grille dag) is applied and dried. A lift-off process digests the resist that remains between the glass and the grille material. The digested resist lifts off the glass, carrying away unwanted grille material on top of it and opening windows in the black grille material. In subsequent coating and photolithographic steps, the red, green, and blue phosphors are deposited in these windows. The result is a patterned luminescent screen with the emissive elements separated by the non-reflecting grille material.

The grille dag and phosphor deposition processes leave a non-uniform screen surface. To level this surface, lacquer is applied as an extrusion film, or it is sprayed onto the screen and then dried. A layer of aluminum is then evaporated onto the screen to enhance reflection.

3.2.3 Shadow mask fabrication and assembly to faceplate

The shadow mask foil is a thin structure made of aluminum-killed steel that is etched with the appropriate pattern of round apertures (may also be slits or slots). It is patterned through a series of photolithographic steps. The mask foil is coated with a casein type resist (a food industry by-product) and exposed with ultraviolet (UV) lamps. The design is developed and the apertures etched away with a ferric chloride solution.[27]

The ferric chloride etchant is reduced by the dissolving iron, producing ferrous chloride from both the etchant and the dissolving iron. The etchant is regenerated using chlorine, producing by-product chemicals and ferric chloride.

[27] The etch process for monitors takes place in Europe or the Pacific-Rim countries. No United States manufacturer has established a high volume, high-resolution shadow mask etching facility.

The mask, which is flat when delivered to the CRT manufacturer, is first curved to approximately the shape of the faceplate in a large hydraulic press. In the CRT, it is supported on a heavy frame, which is typically manufactured by metal cutting, welding and stamping. Springs are welded to the formed frame and the shadow mask is welded on while the parts are held in an alignment fixture. The parts are then oven-blackened to increase the brightness capability of the finished CRT.

3.2.4 Funnel preparation

The funnel provides the back half of the vacuum shell and electrically connects the electron gun in the neck of the CRT and the faceplate to the anode button (a metal connector button in the funnel provided for attachment of the power supply). The conductive coating on the inner surface is an aquadag; similar to the type used on the screen. The major difference is the graphite particle size and the addition of electrical conductivity modifiers. Silicate binder concentration may be higher, and iron oxide may be added, to reduce the conductivity.

Funnel dag is applied by sponge, flow coating, or spraying, and is then baked to evaporate the solvent in the dag. The surface of the dry funnel that will be mated with the faceplate (screen, panel) is coated with a frit (solder glass). This frit is a low melting temperature glass powder made of lead oxide, zinc oxide, and boron oxide, which is mixed with nitrocellulose binder and amyl acetate vehicle to form a paste (with the consistency of toothpaste). It is typically formulated so that the final melting temperature is significantly higher than the original melting temperature, thereby allowing it to be reheated in repair and recovery processes.

3.2.5 Bulb joining

The panel and shadow mask assembly and internal magnetic shield are joined together by clips to form a faceplate assembly. This assembly is placed on the fritted funnel in a fixture that carries the two halves in precise alignment through a high temperature oven, where the frit is cured (hardened). The resulting assembly is a vacuum tight bulb, ready to receive the electron gun and to be evacuated to become a finished CRT.

3.2.6 Electron gun fabrication and assembly

The electron gun is composed of a number of electrostatic field-shaping electrodes made of 300 and 400 series steels. These steels are similar to those used in other industries, but have higher purity requirements and contain iron (Fe), nickel (Ni), and chrome (Cr). The electron gun metals are typically annealed hydrogen fired before being assembled and attached to insulating glass support pillars. The pillars, made of a borosilicate glass, are heated to their softening temperature and pressed over tabs on metal electrodes. After the pillars cool, they captivate the electrodes, making a monolithic structure. This structure is mounted to a glass stem that will be joined to the neck portion of the bulb assembly by melting. The glass stem is provided with electrical feed-though pins, which carry the electrical connections from the external circuitry to the electrodes.

Hidden within the lower end of the gun are three cathodes consisting of hollow nickel tubes, with one end closed and coated with an electron emitting material, typically a mixture of barium, strontium, and calcium carbonates. A tungsten wire heater, coated with a layer of insulating aluminum oxide, is placed in the center of the cathode tube.

Additional ribbon conductors are welded between the upper electrodes and the remaining pins in the stem. Finally, the upper cup of the gun, steel centering springs, and a vacuum getter ring on a long wand are welded on. Additional parts are added at this stage, such as anti-arcing wires, magnet pole pieces, or magnetic shunts, depending upon the design. This finished electron gun assembly is ready for sealing to the bulb.

3.2.7 Final assembly

The frit-sealed bulb assembly and the electron gun assembly are joined by fusing the stem and neck tubing together in a gun-seal machine that melts the two glasses together. During this fusing operation, the two pieces are fixtured into precise alignment. Typically, the neck is slightly longer than necessary and the excess glass is "cut off" by the sealing fires, falls into a reclaim container, and is returned directly to a glass company to be remelted and reformed into a new neck.

Figure 3-4: CRT Manufacturing Process

After joining, the entire CRT is attached to a vacuum exhaust machine that carries the assembly through a high-temperature oven while exhausting the air from inside the CRT. The combination of high temperature while pumping the air out of the CRT produces a high vacuum inside. After cooling, the vacuum getter is vaporized and the evaporated metal (barium, zinc) coats the inside surface of the CRT. This film absorbs the residual gases inside the envelope and reduces the gas pressure inside the CRT to its final operating pressure.

The electron emissive cathode material, which was initially sprayed on the nickel cathode cap as a carbonate, is first converted to an oxide by electrically heating the cathode to high temperature. The surface metal oxides are then reduced to a monolayer of metal by emitting an electrical current from the cathode while it is at high temperature. The resulting surface emits large quantities of electrons that can be controlled by voltages applied to the electrodes of the gun.

The final CRT manufacturing stage is electrical test and visual inspection. Having passed these tests, the CRT faceplate is fitted with a steel implosion band for safety. The band compresses the CRT, thereby increasing the strength of the glass, making the tube more resistant to implosion. A flow-chart description of the CRT manufacturing process is shown in Figure 3-4.[28]

3.3 Active-Matrix LCDs

3.3.1 Thin-film transistor (TFT) structures

Computer displays need very fast response speed, high contrast, and high brightness to handle the information content and graphic demands. One way to achieve this speed is by having a switch at each pixel, which is the basis for active-matrix addressing. This switch can be a transistor or a diode (Appendix A). This profile will cover only the transistor structure, which basically consists of a gate, source and drain, and channel. Electrons flow through the channel between the source and drain when voltage is applied to the gate. There is an insulating layer between the gate and the source/drain region, referred to as a dielectric.

[28] Socolof, M.L., et al., *Environmental Life-Cycle Assessment of Desktop Computer Displays: Goal Definition and Scoping,* (Draft Final), University of Tennessee Center for Clean Products and Clean Technologies, July 24, 1998.

The transistors are patterned on the rear panel of the display, on a base of amorphous silicon (a-Si) or polysilicon (poly-Si). Currently, most flat panel displays (FPDs) use a-Si, although poly-Si does offer some performance advantages in smaller displays. These advantages have not overcome the fact that the technique for depositing thin-film a-Si is very well understood and established. Therefore, most TFT-LCDs are currently based on a-Si, which is the subject of this profile.

TFT a-Si devices are typically characterized as *staggered*, which refers to the fact that the pixel electrodes are on opposite panels (one on the front and one on the rear). More recently, a new design has emerged in the marketplace, called in-plane switching (IPS). This profile will cover the manufacturing processes for the bottom-gate etch stop (E/S)—a staggered structure—and the in-plane switching (ISP) design. Most TFT-LCD monitors are based on the E/S transistor structure, although NEC and Hitachi have released monitors using IPS.

3.3.2 Twisted-nematic TFT-LCD operation

Whereas the E/S or IPS designation relates to the addressing mechanism for each pixel, the principle behind light transmission of the display is related to characteristics of the liquid crystal (LC). This profile covers the operation of twisted nematic (TN) technology, which is used in most computer monitors.

All LCDs work on the same principle: information on the screen is displayed via an array of pixels, controlled by voltage and the orientation of the LC molecules. LC materials are organic compounds that align themselves in the direction of an electric field and have the properties of both solid crystals and viscous liquids. There are almost 400 different types of LC compounds in use for displays. Generally, they are polycyclic aromatic hydrocarbons, or halogenated aromatic hydrocarbons.

The following section describes one way in which light is transmitted or blocked from transmission in a TN-LCD. Figure 3-5 illustrates this process.

Light, which in a TFT-LCD originates from the backlight source or unit, passes through a polarizer before striking the rear panel. This polarizer blocks the transmission of all but a single plane of lightwave vibration. This polarization orientation is parallel to the orientation of the LC molecules and perpendicular to the polarizer plane on the opposite panel. The orientation of the LC is determined by the rubbing direction of the polyimide alignment layers, to which the closest molecules appear to be anchored. The layer on one panel is rubbed at 90 degrees to the other, thereby causing the LC molecular chain to twist 90 degrees between the two panels.

With no voltage applied, the twisted LC structure is fixed. Therefore, light entering from the rear and travelling through the LC cells follows the twist and arrives at the front panel in a plane parallel with this polarizer. As a result, the light is transmitted. When voltage is applied, an electric field is set up between electrodes, one on each of the two panels. The LC molecules align themselves in the direction of the electric field, thereby destroying the twist. The light travels through the cells, arriving at the front panel in a plane perpendicular to the rear polarizer, and is blocked. The field strength will determine how much of the light is blocked, thereby creating a grayscale.

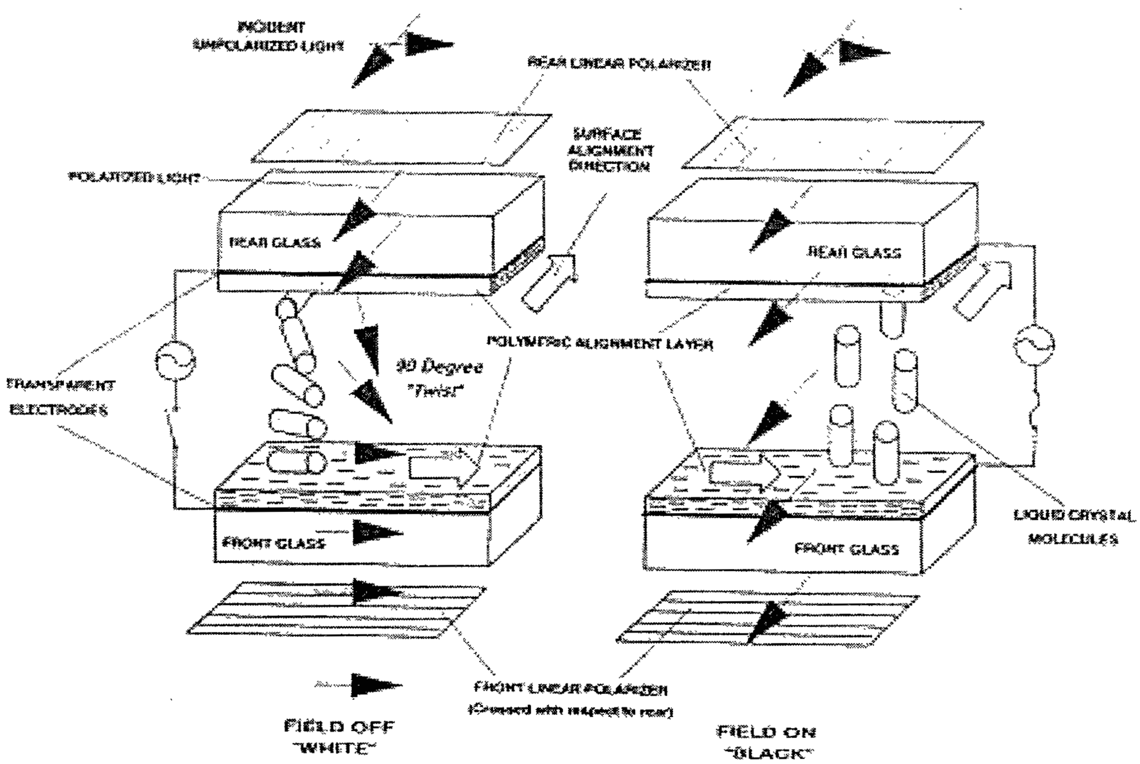

Figure 3-5: TN Field-Effect LCD Operating Principles[29]

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[29] Castellano, J.A., *Handbook of Display Technology*, Academic Press, 1992.

Addressing occurs when the pixels are manipulated with voltage to turn off and on, creating an image on the display screen. The active-matrix LCD uses direct addressing, which requires a switch (the TFT) and a capacitor at each pixel. The TFT is controlled by electrodes, which are the gate and source/drain regions on the transistor. The pixel is addressed by controlling current to the TFT, allowing the transistor to turn on and off. When voltage is applied, there is a short delay while LC molecules align themselves, resulting in a slightly opaque pixel. Also, the capacitor holds the charge for a short period of time after the voltage is removed and the molecules must reorient themselves to their original, 90-degree twist. These delays allow the display to scan the pixels and activate the appropriate ones for the desired image.

The above description is for a black and white display—black, when light is blocked, and white when all wavelengths of incident light is transmitted. Full color results when each pixel is divided into three subpixels— red, green, and blue (RGB). Color filters, which absorb all but a range of wavelengths of the incident light, are used to create the subpixel color. By combining the subpixels, a wide range of color is possible.

3.4 TFT-LCD Manufacturing

The following sections discuss TFT-LCD manufacturing and display assembly processes. This section is designed to provide an overview of these processes only. For available details on equipment and materials used, refer to the TFT-LCD process flow in Appendix D.

3.4.1 Glass fabrication

Molten glass is prepared into flat substrates by the float or fusion draw process. The distinguishing difference between the technologies is the chemical type of the glass required and the degree of flatness. Soda lime glass is acceptable for some LCDs, and borosilicate for others. Whatever the glass material, strict controls are necessary during the glass fabrication process in order to obtain optical quality glass with satisfactory mechanical properties.

The float method of forming glass uses a flat surface, a *bed*, onto which molten glass (the melt) flows. The glass floats on the source of the bed, made of molten tin, becoming flat (sides are parallel) and smooth. In the glass fusion process, the homogeneous melt is drawn downward into a uniform sheet of glass. The speed of the drawing process determines the glass sheet thickness.

After fabrication, the glass sheets are trimmed to the desired size and prepared to withstand upcoming chemical, thermal, and physical activities and to meet high quality standards of optical glass. These activities include some, and perhaps all, of the following: beveling, chamfering, grinding, polishing, and annealing at 350-450 degrees Celsius.

3.4.2 Front panel patterning

Prior to patterning the front panel, the substrate must be clean. The glass is cleaned with physical, chemical, or dry techniques. The list of cleaning methods covers all types that may occur in the LCD panel process. Not all of these cleans occur immediately after the glass manufacturing stage.

Physical cleaning encompasses brush scrubbing, jet spray, ultrasonic, and megasonic methods. The chemical means include cleaning with organic solvents, a neutral detergent, process-specifics cleans according to manufacturing step (etching, stripping, etc.), and pure water cleans following chemical treatment. Dry cleaning processes use ultraviolet ozone, plasma oxide (to clean photoresist residue), non-oxide plasma, and laser energy (limited to localized needs rather than full-surface cleans). Because organic contamination and particulates are significant factors in reduced manufacturing yield, all three methods play important roles at different stages in the process.

3.4.2.1 Deposit ITO

Before creating the necessary layers on the front panel, the glass is physically cleaned, typically using the ultrasonic method. Next, the transparent electrode material, indium tin oxide (ITO), is sputtered onto the substrate. This creates the front panel (common) electrode.

3.4.2.2 Pattern color filter

Next, the black matrix is deposited and patterned, which creates a border around the color filter for contrast. Currently, most TFT-LCDs use a sputtered (physical vapor deposition, or PVD) chrome as the black matrix material, although the trend may be headed toward the use of black resin. The color filters are patterned onto the substrate in succession (RGB), either by spin coating the filter material or by electrodeposition. In each case, the pattern is transferred via the photolithographic process described in Table 3-1. Spin coating is more common than electrodeposition, and the same alternatives to the spin coater mentioned above may be adopted. If a black resin is used for the matrix, it will be applied after the color filter formation, rather than before, as is the case with chrome matrix. The color filter process results in a non-uniform substrate, thereby requiring a planarization step before moving on to the alignment layer creation. The surface is planarized with a layer of polyimide.

3.4.2.3 Deposit alignment layer

The last material to be added to the front panel is the alignment layer, a polyimide that is applied by roll coating and then rubbed to the desired molecular orientation.

3.4.2.4 Inspect and test

The substrate is finally inspected for visual defects and tested.

3.4.3 Rear Panel Patterning

3.4.3.1 Clean and inspect

The rear glass substrate must be cleaned and inspected prior to the detailed and costly patterning processes. Typically, as with the front glass panel, this is accomplished with an ultrasonic water clean.

Coat
Photoresist, a photo-sensitive polyimide resin, is deposited on the substrate, typically using a spin coater. The spin coater dispenses the photoresist into the center of the substrate that is rotating. The centrifugal force resulting from the rotation causes the resist to spread across the substrate toward the edge. This method wastes approximately 90-95 percent of the photoresist material, as most is spun off of the substrate. Several alternative coating techniques have been, or are being, developed.

Prebake
After the photoresist is patterned, the substrate is baked to reduce the moisture content in the photoresist.

Expose
After prebaking, the substrate is ready to be patterned. This is accomplished by placing a mask with the desired pattern on top of the substrate and exposing the photoresist to light of a specific wavelength.

Develop
Depending on the type of photoresist used, specific areas (either those exposed, or those masked) are removed with a developing solution, leaving behind a pattern.

Clean
After developing the pattern, the substrate is cleaned in water to remove chemical residue and then dried.

Bake
The photoresist may be baked once again in order to remove moisture and harden the resist before the upcoming etch step.

Etch
The substrate is now etched to remove the material that was deposited onto the entire substrate and patterned. In this case, the black matrix material (chrome) not covered by photoresist is etched away, leaving a distinct, desired pattern. Depending on the materials to be removed and the linewidth requirements, a wet or dry etch is used. Wet etch involves a solvent immersion or spraying followed by a water clean. Dry etch is a plasma-based reactive ion etch.

Strip/Clean/Inspect
The photoresist is then completely removed from the substrate and cleaned (with water), dried, and inspected. The stripping solution is a solvent, typically either N-methyl pyrrolidinone (NMP) or trimethylamine hydrochloride (TMAH), depending on the type of photoresist.

The patterning process is similar for all standard photolithograhic patterning in semiconductor and LCD manufacturing. The etchants and etching equipment used, however, will vary depending on the material being patterned. A plasma etch may be used for final resist cleaning.

Table 3-1: Standard Photolithographic Patterning Process

3.4.3.2 Pattern TFTs

The rear panel is where the transistors are created, which requires many more steps than the front panel. The transistors are made up of the regions illustrated in Figure 3-6 and discussed below. Each region requires the full photolithographic patterning process. Detailed process flow spreadsheets are provided in Appendix D.

Gate

The gate metal, typically aluminum, is sputtered onto the substrate and patterned. The aluminum may be dry or wet etched.

Gate dielectric/channel/etch stop

The gate SiNx (or SiOx) dielectric, a-Si channel, and SiNx etch stop layer are deposited in succession in a chemical vapor deposition tool. The a-Si is patterned and dry etched.

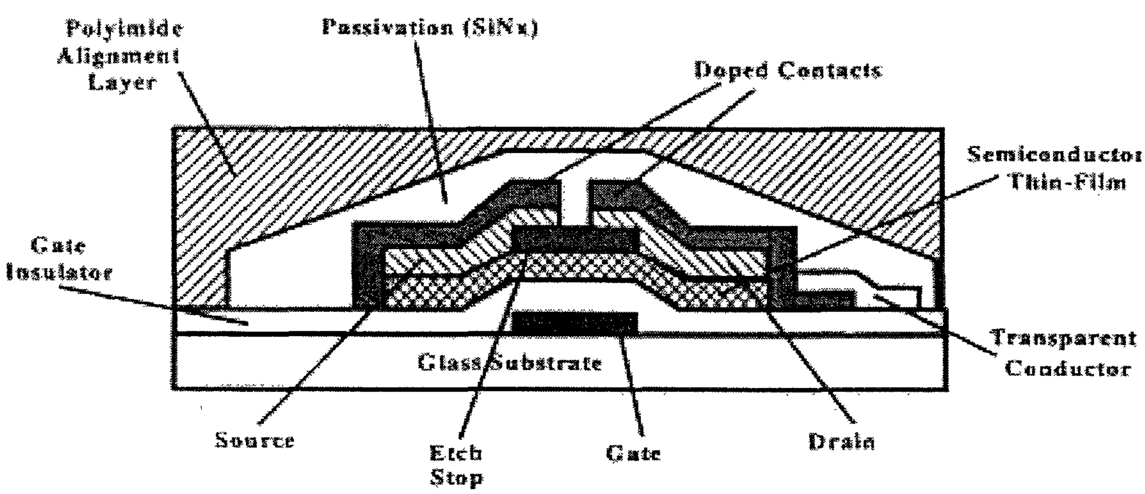

Figure 3-6: Etch/Stop Structure TFT

TFT island

A doped a-Si layer is deposited using CVD, patterned, and dry etched.

Pixel electrode

The pixel electrode is formed by sputtering ITO. The ITO layer is annealed (to reduce film stress) and patterned, using either wet or dry etch.

Contact hole and source/drain metal

A contact between the doped (n+) a-Si layer and the source/drain metals (deposited in the next step) is formed by patterning a hole and etching to expose the n+a-Si. Next, the source/drain metal is sputtered (metal type) and patterned, using either wet or dry etch.

3.4.3.3 Deposit passivation layer/test/inspect

The surface must receive a passivation layer of SiNx for protection, after which the device is inspected and electrically tested.

3.4.3.4 Deposit alignment layer

The substrate is cleaned prior to rubbing to ensure a particulate and contaminant-free surface. Contamination is detrimental to the success of the rubbing process. The thin polymer alignment layer is deposited onto the glass surface by spin coating or printing, and then baked to remove moisture. It is then "rubbed" with fabric in the direction desired for LC orientation. The very fine grooves resulting in the layer help the LC molecules align properly. The rubbing mechanism is typically a cloth on a belt that is attached to a roller, which moves across the substrate, rubbing as it advances. The substrate is then cleaned before moving to the next step.

3.4.4 Front Panel Patterning-IPS

The fabrication of the front panel for the IPS mode display is the same as that described above with one exception: no ITO electrode is formed on the front panel.

3.4.5 Rear Panel Patterning-IPS

The structure described in the following section is a top-gate IPS TFT. The manufacturing advantage is the reduction in the number of mask (patterning) layers from six or seven to potentially four. In the IPS mode, the electrodes are on the same panel. Therefore, the electric field is set up between the pixel and the common (counter) electrodes on the rear panel (see Figure 3-7), rather than between the front and rear of the display (as is the case in the typical TN structure). The LC used in this mode aligns itself horizontally, unlike the vertical alignment of the TN.

Light shield metal

Figure 3-7 illustrates an IPS-mode TFT with a bottom-gate structure. Some IPS designs create the gate at the top of the transistor. In this case, there is a risk of exposing the a-Si layer to backlight energy. This exposure could generate leakage (unwanted) current. Therefore, a layer of chrome is sputtered to act as a light shield. The light shield is patterned and either wet or dry etched.

Dielectric

A passivation layer of SiOx may be deposited through a CVD process. It may be eliminated, as channel protection can be provided by the SiNx layer deposited as part of the island formation.

Source/drain metal

The source/drain metal is sputtered, patterned, and wet etched. This metal can be aluminum (Al)-based, titanium (Ti), molybdenum (Mo), chrome (Cr), tungsten (W), molybdenum/tantalum (Mo/Ta), or Mo/W. The etch process is typically dry (see process flow in Appendix D for etchant chemistry).

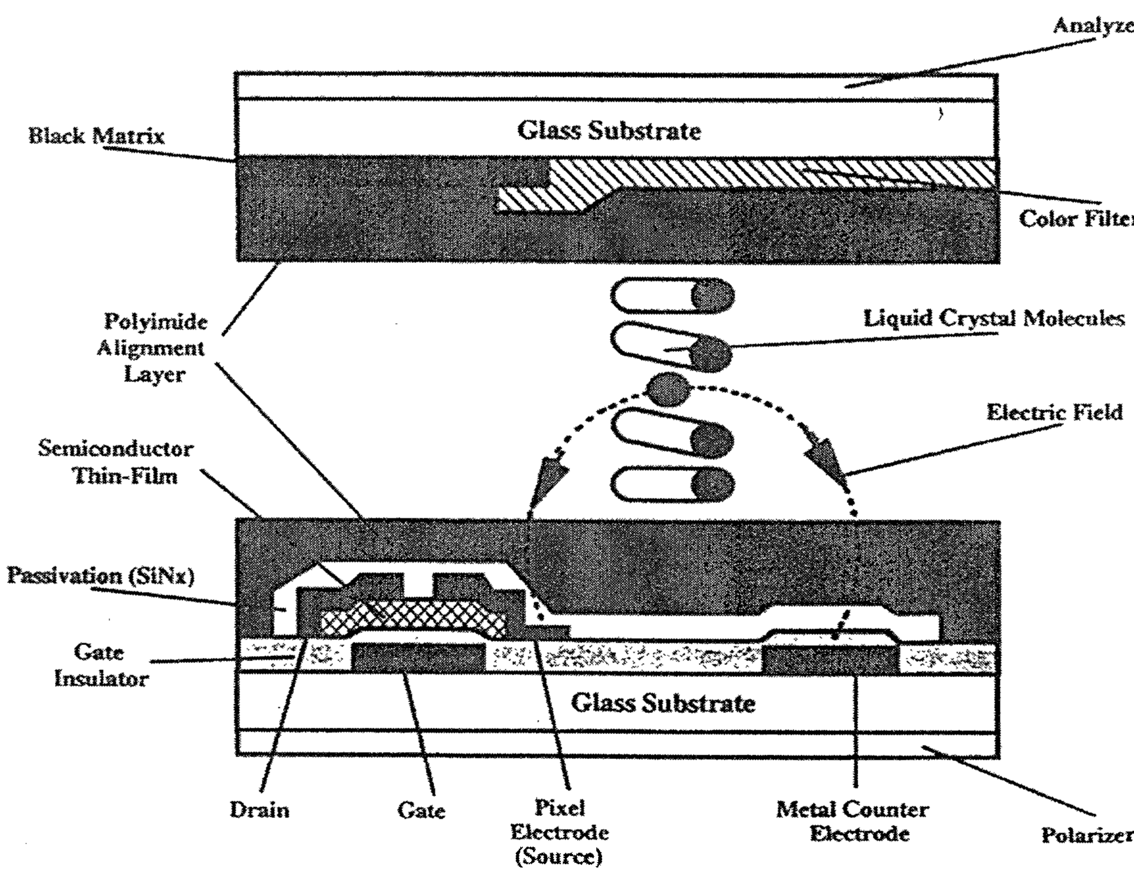

Figure 3-7: Hitachi IPS TFT

Island

The TFT island is created similarly to that for the E/S structure. A single-chamber CVD process is used to deposit a doped (n+) a-Si, a-Si, SiNx combination. The a-Si layer is patterned and dry etched.

Gate, pixel, common electrode

The gate, pixel, and common electrodes are all formed on the rear panel substrate simultaneously, and then patterned in a single mask step. The metal is commonly wet etched.

As with the traditional TN-based rear panel process, following the TFT formation the substrate is coated with an alignment layer and rubbed.

3.4.6 Display cell and final module assembly

At this stage of the process, the color filter substrate (top glass) and TFT substrate (rear glass) are joined with seal material, and liquid crystal (LC) material is injected into the small space in between. Polarizing films are added to the outside of each substrate and the driver electronic PWBs are attached. Finally, the backlight unit is added to complete the display module, the remainder of the electronics is attached, and the entire unit is tested.

3.4.6.1 Seal panels

At this point, the color filter substrate and TFT substrate are ready to be assembled. First, an adhesive seal material is applied, usually by either silkscreening or screen printing. A hole is left in the seal for later LC material injection. After the adhesive is applied, it is cured in order to outgas solvents in the material and achieve partial cross-linking of the polymer. This makes the material less tacky (B-stage material), which allows the plates to touch during alignment.

Before sealing the two substrates (accomplished by lamination), spacers are deposited on one of the substrates to maintain a precise cell gap (between 5-10 micrometers) between the two surfaces. These spacers are either glass or plastic. The substrates are then aligned and laminated by heat and pressure to complete the cross-linking of the polymer.

3.4.6.2 Inject LC

The LC material is injected into the gap produced by the spacer. The hole that was left open for this injection is sealed with the same type of resin and cured.

3.4.6.3 Attach polarizers

The last step in the display cell assembly is the polarizer attachment. The polarizers are typically in rolls or precut sheets, and are applied to the outside of each glass panel with the help of an adhesive layer that is already on one side of the polarizer. The module is cleaned before moving on to inspection and test.

3.4.6.4 Inspect and test

The display module is inspected and functionally tested. The most common display failures can be traced back to particulates and problems with the cell gap.

3.4.7 Module Assembly

3.4.7.1 Attach backlights

The light source for the TFT-LCD is a backlight unit, which is usually a cold cathode fluorescent tube (CCFT). A typical desktop unit has four backlights, which are placed around the edges of the display. A light pipe projects the light across a diffuser screen to provide uniform illumination. If the IPS TFT structure is used, eight backlights are required.

3.4.7.2 Attach electronics

After the cell is inspected and the printed wiring boards (PWBs) are cleaned, the electronics are attached to complete the display module.

Driver chips are attached either on the glass substrate (*chip-on-glass, or COG*) or near it with tape automated bonding (TAB) on flex circuit (*chip-on-film, or COF*). Alternatively, the chips may be mounted on PWBs (*chip-on-board, COB*). The use of TAB bonding for COF device attach is most common. The controller PWB is attached as are other passive components and packaging hardware.

3.4.7.3 Final test and ship

Once all interconnects are attached, the unit goes through a final electrical test and is shipped.

Appendix A

Flat Panel Display Technologies[30]

Technology	Description	Applicability to DfE Project
Liquid Crystal Displays (LCD)	A liquid crystal material, acting like a shutter, blocks, dims, or passes light unobstructed, depending on the magnitude of the electric field across the material.[31] A backlight provides the light source.	Included in the DfE Computer Display Project life-cycle study. Descriptions of the subtechnologies and whether or not they are included in the study are presented below.
(1) Passive matrix (PMLCD)	Liquid crystal (LC) material is sandwiched between two glass plates, which contain parallel sets of transparent electrical lines (electrodes) in a row and column configuration to form a matrix. Every intersection forms a pixel, and the voltage across the pixel causes the LC molecules to align and determines the shade of that pixel.[32]	Traditionally for low-end applications (e.g., calculators, wrist watches). Higher end applications use a super-twisted nematic (STN)[33] construction. The liquid crystal material is twisted between 180 and 270 degrees, which improves the contrast between the "on" and "off" states, resulting in a clearer display than with the twisted nematic (twisted only 90 degrees.[34] However, cost and performance issues limit this technology from wide application in the desktop market, therefore, it will not be evaluated in the study.
(2) Active matrix (AMLCD)	Similar to the PMLCD, except an electronic switch at every pixel provides faster switching and more shades. The addressing mechanism eliminates the viewing angle and brightness problems suffered by PMLCD. Requires more backlight than PMLCD due to the additional switching devices on the glass (at each pixel). Various switching types are listed below:	Provides vivid color graphics in portable computer and television screens.[35] This technology meets the functional unit specifications in this study. Specific subcategories are described below.

30 Socolof, M.L., et al., Environmental Life-Cycle Assessment of Desktop Computer Displays: Goal Definition and Scoping, (Draft Final), University of Tennessee Center for Clean Products and Clean Technologies, July 24, 1998.

31 Office of Technology Assessment, *Flat Panel Displays in Perceptive*, OTA-ITC-631, Washington, DC: U.S. Government Printing Office, September, 1995.

32 Ibid.

33 Traditional light modulating methods for LCD technologies include twisted nematic (TN), super-twisted nematic (STN), double STN, triple STN, and film-compensated STN. The STN is the current standard for high-end PMLCD applications.

34 Office of Technology Assessment, *Flat Panel Displays in Perceptive*, OTA-ITC-631, Washington, DC: U.S. Government Printing Office, September, 1995.

35 Ibid.

Technology	Description	Applicability to DfE Project
	AMLCD Switch Types:	
	(2a) Thin-film transistor (TFT): The transistor acts as a valve allowing current to flow to the pixel when a signal is applied. The transistors are made of various materials including: amorphous silicon (a:Si), polycrystalline silicon (p:Si), non-Si[CdSe].[36] Two different TFT light modulating modes are twisted nematic (TN) and in-plane switching (IPS).[37] In comparison to the TN mode, the IPS mode requires more backlight but fewer manufacturing steps.	The current standard AMLCD switching mechanism for computer displays is a:Si TFT. Polycrystalline Si is not suitable for larger than about 5" displays. Both the TN and IPS a:Si TFT AMLCD technologies are analyzed in the DfE project.
	(2b) Diode matrix: The diode acts as a check valve. When closed, it allows current to flow to the pixel charging it. When opened, the pixel is disconnected and the charge is maintained until the next frame.[38]	The diodes are found to short easily and must be connected in series to achieve long life usability. The diode displays are also limited in size to smaller than that of the functional unit defined for the DfE study.
	(2c) Metal-insulator metal (MIM): The MIM is a diode type switch using metal-insulated-metal fabrication techniques.[39]	Temperature sensitive, which creates gray scale nonuniformities. They are also size-limited, like other diode type displays and therefore not included in the study.
(3) Active-addressed LCD	Hybrid of passive and active matrix. The pixels are addressed using signals sent to the column and row as determined using an algorithm encoded into an integrated circuit (IC). The IC drives each row of pixels more or less continuously and drives multiple rows at one time.[40]	Employed in notebook and desktop monitors >12.1". However, they need special drivers[41] have slow response times, and their contrast worsens as panel size increases. Therefore, this technology does not meet the specifications of the functional unit and is excluded from evaluation in the DfE study.
(4) Plasma-addressed liquid crystal (PALC)	The pixel is addressed using row electrodes, which send the signal, and column gas channels, which conduct a current when ionized.[42]	PALC displays are in development to be used as large low cost displays. Production of the displays have not yet occurred and they are not included in the study.

[36] Castellano, J., *Handbook of Display Technology,* Stanford Resources, Inc., San Jose, CA., 1992.
[37] *DsiplaySearch FPD Equipment and Materials Analysis and Forecast,* Austin, TX, 1998.
[38] Castellano, J., *Handbook of Display Technology,* Stanford Resources, Inc., San Jose, CA., 1992.
[39] Office of Technology Assessment, *Flat Panel Displays in Perceptive,* OTA-ITC-631, Washington, DC: U.S. Government Printing Office, September, 1995.
[40] Ibid.
[41] Ibid.
[42] Ibid.

Technology	Description	Applicability to DfE Project
(5) Ferroelectric LCDs (FLCD or FELCD)	The pixel is addressed using positive or negatives pulses to orient the crystals. The positive pulse allows light to pass (light state) and the negative pulse causes the blockage of light (dark state).[43] A ferroelectric liquid crystal is bistable and holds its polarization when an electric field is applied and removed.[44] They are also called surface stabilized ferroelectric (SSF) LCDs.	Has high resolution with very good brightness, but limited color palette.[45] Limited color palette does not meet color specification of functional unit.
Plasma Display Panels (PDP)	An inert gas (e.g., He, Ne, Ar) trapped between the glass plates emits light when an electric current is passed through the matrix of lines on the glass. Glow discharge occurs when ionized gas undergoes recombination. Ionization of atoms occurs (electrons are removed), then electrons are recombined to release energy in the form of light. Full color plasma displays use phosphors that glow when illuminated by the gas.[46]	Established technology. Good for large screens (e.g., wall-mounted televisions), but are heavier and require more power than LCDs.[47] Designed for large screens and are larger displays than specified for desktop applications. Therefore, not included in the study.
Electroluminescent Displays (EL)	A phosphor film between glass plates emits light when an electric field is created across the film.[48] EL uses a polycrystalline phosphor (similar to LED technology, which is also an electroluminescent emitter, but uses a single crystal semi-conductor). ELs are doped (as a semiconductor) with specific impurities to provide energy states that lie slightly below those of mobile electrons and slightly above those of electrons bound to atoms. Impurity states are used to provide initial and final states in emitting transitions.[49] Also referred to as thin-film EL (TFEL). Variations: AC thin-film EL (AC-TFEL), active matrix EL (AMEL), DC EL, organic EL.	Lightweight and durable. Used in emergency rooms, on factory floors, and in commercial transportation vehicles.[50] Problems found in the power consumption and controlling of gray levels. Targeted toward military, medical, and high-end commercial products; therefore not included in the scope of the DfE project.

[43] Castellano, J., *Handbook of Display Technology*, Stanford Resources, Inc., San Jose, CA., 1992.
[44] Peddie, Jon, *High Resolution Graphics Design Systems*, McGraw Hill, New York, NY, 1994.
[45] Ibid.
[46] Office of Technology Assessment, *Flat Panel Displays in Perceptive*, OTA-ITC-631, Washington, DC: U.S. Government Printing Office, September, 1995.
[47] Ibid.
[48] Ibid.
[49] Peddie, Jon, *High Resolution Graphics Design Systems*, McGraw Hill, New York, NY, 1994.
[50] Office of Technology Assessment, *Flat Panel Displays in Perceptive*, OTA-ITC-631, Washington, DC: U.S. Government Printing Office, September, 1995.

Technology	Description	Applicability to DfE Project
Field Emission Displays (FED)	Flat CRT with hundreds of cathodes (emitters) per pixel (form of cathodeluminescent display); eliminates single scanning electron beam of the CRT. Uses a flat cold (i.e., room temperature) cathode to emit electrons. Electrons are emitted from one side of the display and energize colored phosphors on the other side.[51]	Not commercially available, but anticipated to fill many display needs.[52] Could potentially apply in all LCD and CRT applications. High image quality as with CRT, but less bulky and less power use than with CRT. A number of roadblocks to this technology taking over the AMLCD market include proven manufacturing processes (problems found in the reliability and reproducibility of the devices), efficient low-voltage phosphors, and high voltage drivers. The technology is targeted toward military, medical and high-end commercial products and not included in the DfE study.
Vacuum Fluorescent Displays (VFD)	Form of cathodeluminescent display that employs a flat vacuum tube, a filament wire, a control grid structure, and a phosphor-coated anode. Can operate at low voltages, because very thin layers of highly efficient phosphors are coated directly onto each transparent anode.[53]	VFDs offer high brightness, wide viewing angle, multi-color capability, and mechanical reliability. Used in low information content applications (e.g., VCRs, microwaves, audio equipment, automobile instrument panels). No significant uses seen for computer displays.[54]
Digital Micromirror Devices (DMD)	Miniature array of tiny mirrors built on a semiconductor chip. The DMD is used in a projector that shines light on the mirror array. Depending on the position of a given mirror, that pixel in the display reflects light either onto a lens that projects it onto a screen (resulting in a light pixel) or away from the lens (resulting in a dark pixel).[55]	Just beginning to be used mainly as projection devices, and has not been developed for use that would match the functional unit of the DfE study.[56]

[51] Office of Technology Assessment, *Flat Panel Displays in Perceptive*, OTA-ITC-631, Washington, DC: U.S. Government Printing Office, September, 1995.

[52] Ibid.

[53] Peddie, Jon, *High Resolution Graphics Design Systems*, McGraw Hill, New York, NY, 1994.

[54] Ibid

[55] Office of Technology Assessment, *Flat Panel Displays in Perceptive*, OTA-ITC-631, Washington, DC: U.S. Government Printing Office, September, 1995.

[56] Ibid.

Technology	Description	Applicability to DfE Project
Light Emitting Diodes (LED)	The LED device is essentially a semiconductor diode, emitting light when a forward bias voltage is applied to a p-n junction. The light intensity is proportional to the bias current and the color dependent on the material used. The p-n junction is formed in a III-V group material, such as aluminum, gallium, indium, phosphorous, antimony, or arsenic.	For low information display applications, which makes it not capable of meeting the requirements of the functional unit of the study. Color, power, and cost limitations prevent the emergence into the high information display market.[57]
Electrochromic Display	Open-circuit memory using liquid electrolytes.[58] Non-emitter (as LCDs), as opposed to emitters (e.g., EL, FED, PDP).	Outstanding contrast and normal and wide viewing angles, open-circuit memory. Complex and costly, involving liquid electrolytes, poor resolution, poor cycle life, lack of multicolor capability, etc. Not suitable for computer displays in past; however, new technology may be promising.[59]
Light Emitting Polymers	Developing technology (Holton 1997).[60]	Developing technology.

[57] Castellano, J., *Handbook of Display Technology*, Stanford Resources, Inc., San Jose, CA., 1992.
[58] Peddie, Jon, *High Resolution Graphics Design Systems*, McGraw Hill, New York, NY, 1994.
[59] Ibid.
[60] Holton, W.C., "Light-emitting polymers: increasing promise," *Solid State Technology*, vol. 40, no.. 5, p. 163, May 1997.

Appendix B

CRT Manufacture

Process step	Equipment	Process Material/Chemical	Notes
Fabricate glass			
Mix batch			
Melt			
Fine			
Condition			
Form panel			
Anneal			
Finish			
Clean			
Cut			
Grind and polish			
Inspect			
Test			
Pattern panel glass			
Clean			
Etch		acid	
Apply (contrast) grille material	spin coat	aquadag (polyvinyl alcohol)	1
Dry aquadag			
Apply green phosphor slurry	spin coat	slurry mixture: water, wetting agents, polyvinyl alcohol	
Dry phosphor	IR lamp		
Expose green phosphor	near-UV lamps		
Develop		water	
Dry			
Apply blue phosphor slurry	spin coat	ZnS:Ag	
Expose blue phosphor	near-UV lamps		
Develop		water	
Dry			
Apply red phosphor slurry	spin coat	Y_2O_2S:Cu	
Expose red phosphor	near-UV lamps		
Develop		water	
Dry			
Apply lacquer leveling film	spin coat or spray	polymer	
Apply reflective layer	evaporate	aluminum	1000 angstroms

Process step	Equipment	Process Material/Chemical	Notes
Prepare funnel			
Coat inside of funnel (dag)	sponge, flow coat, or spray	aquadag	2
Dry coating	evap oven		
Apply frit		Pb glass frit (PbO, ZnO, BO), nitrocelluose binder, amyl acetate	
Harden	evap oven	remove amyl acetate	
Manufacture shadow mask		rolled iron or Invar metal	
Etch hole pattern		etchant: ferric chloride solution	
Clean		water	
Anneal			
Draw to face plate contour			
Blacken mask and side pieces			
Weld side pieces			
Anneal magnetic shield	oven		
Blacken shield	oven		
Manufacture electron gun			3
Hydrogen fire metals			
Fixture metal parts			
Heat glass pillars			4
Press pillars over tabs on electrode			
Mount to glass stem			
Join stem to neck	melt		
Insert cathodes into support pins			
Insert heater			
Manufacture electron gun			
Weld assembly to support pins			
Weld ribbon conductors			
Weld centering springs, getter			
Add additional parts			5
Assemble mask to panel		aluminum-killed steel	
Coat shadow mask back side		bismuth oxide	
Curve shadow mask	hydraulic press		
Weld springs (brackets) to frame			
Weld mask			
Position shield on brackets			

Process step	Equipment	Process Material/Chemical	Notes
Join bulb and gun			
Attach panel to funnel	clips		total layer <.002 inch
Cure frit			> 440 °C
Seal gun to bulb			fuse base to funnel neck
Exhaust/finish assembly			
Cut excess neck glass			
Evacuate	vacuum exhaust		6
Heat tube			350 °C
Notes:			
(1) Electrically conductive carbon materials (graphite) w/silicate binders in water suspension.			
(2) Aquadag with addition of electrical conductivity modifiers, higher concentration of silicate binder, and possibly iron.			
(3) 300/400 series steels (contain Fe, Ni, Cr); borosilicate glass insulation; Ni cathode; mix. of Ba, Sr, Ca carbonates emitter material; W wire heater coated with Al oxide.			
(4) Glass pillars heated to softening temperatures.			
(5) Arcing wires, magnet pole pieces, magnetic shunts.			
(6) Excess neck glass is reused by glass companies.			

Appendix C

NEC CRT: Detailed Bill of Materials

NEC JC-1549VNA

Sub No. Entry No.	Name	Qty.	Material	Weight (grams)	Total (grams)
Bill of Materials for: NEC JC-1549VNA					
1.1	chassis	1	PS	1624.9	1624.9
1.2	right hand shield	1	steel	499.2	499.2
1.3	left hand shield	1	steel	417.4	417.4
1.4	top shield	1	steel	64.5	64.5
1.5	insulator pad	1	polyester	27.2	27.2
1.6	back shield	1	steel	190.5	190.5
1.7	shield brackets	4	brass	4	16
1.8	screws	46	zinc plated steel	1.6	73.6
1.9	swivel base large	1	PS	272.2	272.2
1.10	rubber feet	4	silicone rubber	0.5	2
1.11	brackets	4	brass	1	4
1.12	swivel base small	1	PS	109.9	109.9
1.13	base shield	1	steel	1079.5	1079.5
1.14	base bracket	2	PS	46.4	92.8
1.15	shadow mask	1	steel	626	626
1.16	anode connection	1	steel	3.3	3.3
1.17	anode cap	1	rubber	16.4	16.4
1.18	anode cap insert	1	steel	3.6	3.6
1.19	glass	1	glass	5511.1	5511.1
1.20	bracket 1	1	steel	46.4	46.4
1.21	bracket 2	1	steel	90.7	90.7
1.22	bracket 4	1	steel	246.7	246.7
1.23	xy control 1	1	PC	9.4	9.4
1.24	xy control 2	1	PC	6.2	6.2
Bill of Materials for: Neck assembly					
2.1	base neck	1	PS	66.9	66.9
2.2	top neck	1	PS	15.9	15.9
2.3	neck ring large 1	1	PS	15	15
2.4	neck ring small 1	1	PS	4.5	4.5
2.5	neck ring small 2	1	PS	4	4
2.6	meck ring large 2	1	PS	14.5	14.5
2.7	ferrite magnet	1		295.6	295.6
2.8	Cu attached to magnet	1	copper	134.5	134.5
2.9	Cu attached to neck	1	copper	108.9	108.9
2.10	extraneous copper	1	copper	0.4	0.4
2.11	insulating rings	4	polysulphone	4.1	16.4
2.12	brass ring	1	brass	2.1	2.1
2.13	rubber gaskets	2	rubber	6	12
2.14	screw with washers	4	zinc plated steel	2.9	11.6

Sub. No. Entry No.	Name	Qty.	Material	Weight (grams)	Total (grams)
2.15	neck clamp	1	steel	4.4	4.4
2.16	brackets	4	brass	1.2	4.8
Bill of Materials for: Gun					
3.1	gun	1	steel	19.4	19.4
3.2	brackets	2	PC	2.9	5.8
3.3	attachment to glass	1	plastic	2.9	2.9
3.4	attachment to board 1	1	polycarbonate	4.2	4.2
3.5	attachment to board 2	1	polycarbonate	10.9	10.9
3.6	connectors	2	aluminum	0.4	0.8
3.7	screws	4	zinc plated steel	0.9	3.6
3.8	shield	1	steel	79.4	79.4
3.9	PWB board 194 mm x 122 mm	1	4 layer		
3.9a	heat sink	4	aluminum	17.6	70.4
3.9b	SOP	1			
3.9c	resistors	117			
3.9d	capacitors	60			
3.9e	transistors	27			
3.9f	resistors	4	7W		
3.9g	variable resistors	9			
3.9h	jumpers	7			
3.9i	connector 12 pin	1			
3.9j	connector 6 pin	1			
3.9k	connector 2 pin	2			
Bill of Materials for: Power board					
4.1	flyback transformer	1		320.8	
4.1a	wire	1	440 mm		
4.1b	connector 2 pin	1			
4.1c	wire	2	172 mm		
4.1d	wire	1	194 mm		
4.1e	magnet	1	ferrite magnet	101.6	101.6
4.1f	steel pin	1	steel	3.8	3.8
4.1g	rubber cap	1	rubber	1	1
4.1h	misc. potting material	1	silicone	176.2	176.2
4.1i	copper wire	1	copper	38.2	38.2
4.2	PWB additional 194mm x 95 mm	1	4 layer		
4.2a	capacitors	47			
4.2b	SOP	9			
4.2c	transistors	12			
4.2d	resistors	149			
4.2e	jumpers	6			
4.2f	wire	5	156 mm		
4.2g	connectors 5 pin	2			
4.3	PWB (x controller)		2 layer		
4.3a	PWB	1	114 x 20 mm		

Sub. No. Entry No.	Name	Qty.	Material	Weight (grams)	Total (grams)
4.3b	inductor	1	copper	5.4	5.4
		1	baclite	4.6	4.6
4.3c	wire	2	156 mm		
4.3d	3 pin connector	1			
4.4	PWB (y controller)		2 layer		
4.4a	PWB	1	35 x 74 mm		
4.4b	wire	2	156 mm		
4.4c	3 pin connector	1			
4.4d	resistor	1			
4.5	knobs sm	5	PS	2.8	14
4.6	knobs lg	2	PS	4.4	8.8
4.7	aluminum shielding	1	aluminum	136.3	136.3
4.8	heat sink 1	1	aluminum	20.7	20.7
4.9	heat sink 2	1	aluminum	38.9	38.9
4.10	heat sink 3	1	aluminum	15.2	15.2
4.11	edge bracket	1	steel	87.2	87.2
4.12	wire	12	32 mm		
4.13	connector 12 pin	2			
4.14	PWB power, 349.5 x 245 mm	1	4 layer		
4.14a	fuse	1			
4.14b	variable resistors	1			
4.14c	resistors	251			
4.14d	capacitors	165			
4.14e	transistors	28			
4.14f	SOP	8			
4.14g	diode	1			
4.14h	junpers	25			
4.14i	inductor	1	baclite	6.8	6.8
		1	copper	9.6	9.6
		1	ferrite	7.6	7.6
	insulating tape	1	polyester	0.6	0.6
4.14j	inductor	1	baclite	8.7	8.7
		1	copper	26.8	26.8
		1	ferrite	139.5	139.5
4.14k	copper tape	1	copper	2.4	2.4
4.14 l	inductor	1	baclite	9.5	9.5
		1	copper	12	12
		1	ferrite	8.5	8.5
	insulating tape	1	polyester	4.8	4.8
4.14m	inductor	1	baclite	5.7	5.7
		1	copper	7.2	7.2
		1	ferrite	5.1	5.1
	insulating tape	1	polyester	0.5	0.5
4.14n	inductor	1	baclite	3.8	3.8
		1	copper	4.8	4.8
		1	ferrite	3.4	3.4

Sub No. Entry No.	Name	Qty.	Material	Weight (grams)	Total (grams)
	insulating tape	1	polyester	0.4	0.4
4.14 o	inductor	2	ferrite magnet	17.9	35.8
		2	copper	1.8	3.6
4.14p	inductor	2	baclite	5.4	10.8
		2	copper	4.6	9.2
		2	ferrite	4.2	8.4
4.14q	connector 15 pin	2			
4.14r	connector 3 pin	2			
4.14s	connector 5 pin	4			
4.14t	connector 6 pin	1			
4.14u	connector 2 pin	2			
4.14v	connector 4 pin	1			
4.14w	wire	4	296 mm		
4.15	power switch	1	PS	5.2	5.2
4.16	power cord receptacle	1	ABS	34	34
4.17	power cord	1	475 mm length	292.7	292.7
Bill of Materials for: PWB attached to power board by cable connector					
5.1	PWB, 82 x 30 mm	1	4 layer		
5.2	SOP	1			
5.3	resistors	2			
5.4	capacitors	4			
5.5	transistors	1			
5.6	connector 5 pin	1			
Bill of Materials for: PWB attached to power board by solder connector					
6.1	PWB, 53 x 52 mm	1	2 layer		
6.2	SOP	1			
6.3	resistors	24			
6.4	capacitors	10			
6.5	transistors	6			
6.6	connector 13 pin	1			
6.7	jumpers	4			
Bill of Materials for: PWB attached to power board by solder connector					
7.1	PWB, 44 x 96 mm	1	2 layer		
7.2	SOP	2			
7.3	resistors	37			
7.4	capacitors	11			
7.5	transistors	5			
7.6	connector 11 pin	1			
7.7	jumpers	2			
				Weight Total	11636.8

Appendix D

TFT-LCD Manufacture

Glass Panel

Process Step	Equipment	Material/Chemical	Notes
Fusion Method		barium borosilicate, aluminoborosilicate; 0.7mm thick	e.g., Corning 7059: 49% SiO_2, 10% Al_2O_3; 15% B_2O_3; 25% BaO; 1% other
Mix			
Melt glass			
Fine			
Condition			
Flow glass			
Draw glass			
Cut glass	band, wire, or circular blades		
Bevel/chamfer/heat glass			
Grind (may be eliminated)		sand, garnet, corundem, silicon, carbide, boron carbide, or diamond	
Polish (may be eliminated)			
Chemical finishing		potassium nitrate	
Clean (physical)	brush, scrub, ultrasonic, or megasonic		
or Clean (chemical)		organic solvent; neutral detergent; or chemical clean; and water	
or Clean (dry)	ultraviolet ozone; plasma oxide; plasma non oxide; or laser		
Anneal (back panel only)			350-400°C
Float method		barium borosilicate or aluminoborosilicate; 0.7mm thick	e.g., Corning 7059: 49% SiO_2, 10% Al_2O_3; 15% B_2O_3; 25% BaO; 1% other
Mix			
Melt			
Fine			
Flow glass	molten tin bed	float on bed of molten tin in chemically controlled atmosphere	
Cool glass		still on molten tin	
Cut glass			
Bevel/chamfer/heat glass			
Grind (may be eliminated)			
Polish (may be eliminated)			
Chemical finishing		potassium nitrate	
Clean (physical)	brush, scrub, ultrasonic, or megasonic		
or Clean (chemical)		organic solvent; neutral detergent; or chemical clean; and water	
or Clean (dry)	ultraviolet ozone; plasma oxide; plasma non oxide; or laser		
Anneal (back panel only)			

Front Panel Pattern-TN

Process Step	Equipment	Process Material	Ancillary Material	Notes
Clean glass	Ultrasonic clean/spin rinse dryer		IPA, water, nitrogen	
Deposit ITO	PVD		Indium tin oxide	
Coat photoresist	Spin coater		Polyimide	
Bake	Oven			
Expose	Stepper			
Develop	Developer		TMAH	
Clean	Spin rinse dryer		Water	
Bake photoresist	Oven			
Etch ITO	Plasma etcher		Cl_2; HBr; He; O_2	Wet etch: HCL
Strip photoresist	Developer		TMAH	
Clean	Spin rinse dryer		Water	
Deposit black matrix material	Sputter	Chrome		Alternative: black resin & photo process
Coat photoresist	Spin coater		Polyimide	
Bake	Oven			
Expose	Stepper			
Develop	Developer		TMAH	
Clean	Spin rinse dryer		Water	
Bake	Oven			
Etch Cr	Wet bench			
Strip photoresist	Wet bench		TMAH	
Clean	Spin rinse dryer		Water	
Inspect				
Apply (R) color filter material	Extrude/spin or slit/spin coater	0.8-2.0 um acryl epoxy resin, Sbq-PVA	Same as process material	Pigment-dispersion method, 99% TFTs
Bake	Oven			
Expose	Stepper			
Develop	Developer		TMAH	
Clean	Spin rinse dryer		Water	Negative resist; extra strip not required
Apply (G) color filter material	Spin coater	Pigment-diffused acryl epoxy resin	Same as process material	
Bake	Oven			
Expose	Stepper			
Develop	Developer		TMAH	
Clean	Spin rinse dryer		Water	
Apply (B) color filter material	Spin coater	Pigment-diffused acryl epoxy resin	Same as process material	
Expose	Stepper			
Develop	Developer		TMAH	
Clean	Spin rinse dryer		Water	

Process Step	Equipment	Process Material	Ancillary Material	Notes
Deposit alignment layer	Roll coat	Polyvinyl alcohol; polyesters; poly- siloxanes; polyamic acid solution		
Bake	Oven			
Rub	Rubbing machine			
Inspect	Microscope			
Test				

Rear Panel Pattern-TN

Process Step	Equipment	Product Materials	Ancillary Materials	Notes
Clean bottom glass	Ultrasonic or brush		IPA, nitrogen, water	alkali-free likely future material
Inspect				
Deposit gate metal	PVD	One of the following: Al, Al + barrier, Al + metal, Al alloy		Ti/Al/Ti possible future metal layers
Coat photoresist	Spin coater		Polyimide	90- 95% wasted on traditional spin coater
Bake	Oven			
Expose	Stepper			
Develop	Developer		NMP	
Clean	Spin rinse dryer		Water	
Bake photoresist	Oven			
Etch gate metal	Plasma etcher			or wet etch + clean
			Al: Cl_2+BCl_3/Cl_2	
			Al+barrier: Cl_2; BCl_3; N_2; CF_4	
			Al+metal: Cl_2; BCl_3; N_2; CF_4	
			Al alloy (Zr, Cu, Nd, Y): Cl_2; BCl_3; N_2; CF_4	
Strip photoresist	Developer		NMP	
Clean	Spin rinse dryer		Water	
Inspect				
Deposit dielectric material	PECVD	SiO_2 or SiN		
Deposit channel material	PECVD	a-Si		
Deposit etch stop layer	PECVD	SiNx		
Coat photoresist	Spin coater		Polyimide	
Bake	Oven			
Expose	Stepper			
Develop	Developer		NMP	
Clean	SRD		Water	
Bake photoresist	Oven			
Etch SiNx	Plasma etcher		CHF_3; CF_4	
Etch a-Si	Plasma etcher		CF_4; O_2	
Etch SiNx	Plasma etcher		CF_4; O_2 or Cl_2	
Strip photoresist	Developer		NMP	
Clean	SRD		Water	
Deposit ohmic contact material	PECVD	Doped Si (n-type: As,P)		
Coat photoresist	Spin coater		Polyimide	
Bake	Oven			
Expose	Stepper			

Process Step	Equipment	Product Materials	Ancillary Materials	Notes
Develop	Developer		NMP	
Clean	SRD		Water	
Bake photoresist	Oven			
Etch doped a-Si	Plasma etcher		Cl_2 or CF_4+O_2 or SF_6+HCL	
Strip photoresist	Developer		NMP	
Clean	Spin rinse dryer		Water	
Deposit ITO	PVD	Indium oxide/tin oxide		
Anneal	Oven			
Coat photoresist	Spin coater		Polyimide	
Bake	Oven			
Expose	Stepper			
Develop	Developer		NMP	
Clean	SRD		Water	
Bake photoresist	Oven			
Etch ITO	Plasma etcher		Cl_2+ HBr; He; O_2; CH_4+H_2	or wet etch + clean
Strip photoresist	Developer		NMP	
Clean	SRD		Water	
Coat photoresist	Spin coater		Polyimide	
Bake	Oven			
Expose	Stepper			
Develop	Developer		NMP	
Clean	SRD		Water	
Bake photoresist	Oven			
Etch n+ a-Si (contact)	Plasma etcher		Cl_2	
Deposit source/drain metal	PVD	One of the following: Al, Al + barrier, Al + metal, Al alloy Ti, Mo, Cr, W, MoTa, or MoW		
Coat photoresist	Coater		Polyimide	
Bake	Oven			
Expose	Oven			
Develop	Stepper			
Clean	Developer		NMP	
Bake photoresist	Spin rinse dryer		Water	
Etch metal	Plasma etcher		Al etch: Cl_2+BCl_3/Cl_2	or wet etch + clean
			Al+barrier: Cl_2; BCl_3; N_2; CF_4	
			Al+metal: Cl_2; BCl_3; N_2; CF_4	
			Al alloy (Zr, Cu, Nd, Y): Cl_2; BCl_3; N_2; CF_4	
Strip photoresist	Developer		NMP	
Clean	SRD		Water	
Deposit passivation layer	PECVD	SiNx	CF_4+O_2	
Coat photoresist	Coater		Polyimide	
Bake	Oven			
Expose	Oven			

Process Step	Equipment	Product Materials	Ancillary Materials	Notes
Develop	Proximity printer			
Clean	Developer		NMP	
Bake photoresist	SRD		Water	
Etch SiNx	Plasma etcher		O_2, N_2, He, SiF_6, CHF_3 (mixture)	
Strip photoresist			NMP	
Clean	SRD		Water	
Deposit alignment material	Roll coater	Polyimide, 500 to 1000 A		
Bake	Oven			
Rub	Rubbing machine			
Electrostatic discharge				
Test	SRD		Water	

Front Panel Pattern-IPS

Process Step	Equipment	Process Material	Ancillary Material	Notes
Clean glass	Ultrasonic clean/SRD		IPA, water, nitrogen	
Deposit black matrix material	Sputter	Chrome		Alternative: black resin & photo process
Coat photoresist	Spin coater		Polyimide	
Bake	Oven			
Expose	Stepper			
Develop	Developer		TMAH	
Clean	Spin rinse dryer		Water	
Bake	Oven			
Etch Cr	Wet bench			
Strip photoresist	Wet bench		TMAH	
Clean	Spin rinse dryer		Water	
Inspect				
Apply (R) color filter material	Extrude/spin or slit/spin coater	0.8-2.0 um acryl epoxy resin, Sbq-PVA	Same as process material	Pigment-dispersion method, 99% TFTs
Bake	Oven			
Expose	Stepper			
Develop	Developer		TMAH	
Clean	Spin rinse dryer		Water	Negative resist; extra strip not required
Apply (G) color filter material	Spin coater	Pigment-diffused acryl epoxy resin	Same as process material	
Bake	Oven			
Expose	Stepper			
Develop	Developer		TMAH	
Clean	Spin rinse dryer		Water	
Apply (B) color filter material	Spin coater	Pigment-diffused acryl epoxy resin	Same as process material	
Expose	Stepper			
Develop	Developer		TMAH	
Clean	SRD		Water	
Deposit alignment layer	Roll coat	Polyvinyl alcohol; polyesters; poly-siloxanes; polyamic acid solution		
Bake	Oven			
Rub	Rubbing machine			
Inspect	Microscope			
Test				

Rear Panel Pattern-IPS

Process Step	Equipment	Product Materials	Ancillary Materials
Clean substrate	Brush, disk, US, or MS		
Inspect			
Deposit light shield metal	PVD	Cr	
Coat photoresist	Coater		Positive photoresist
Bake	Oven		
Expose	Stepper		
Develop	Developer		NMP
Clean	Spin rinse dryer		Water
Bake	Oven		
Etch Cr	Plasma etcher	$Cl_2;O_2$	
Strip	Plasma asher	$Cl_2;O_2$ (or wet bench)	
Clean	Spin rinse dryer		
Inspect	AOI		
Deposit dielectric	CVD	SiO_2	
Deposit source/drain metal	PVD	One of the following: Al, Al + barrier, Al + metal, or Al alloy	
Coat photoresist	Coater		
Bake	Oven		
Expose	Stepper		
Develop	Developer		NMP
Clean	Spin rinse dryer		Water
Bake	Oven		
Etch			Al etch: $C1_2+BC1_3/C1_2$
			Al+barrier: Cl_2; BCl_3; N_2; CF_4
			Al+metal: Cl_2; BCl_3; N_2; CF_4
			Al alloy (Zr, Cu, Nd, Y): Cl_2; BCl_3; N_2; CF_4
Strip			NMP
Clean			Water
Create island		SiNx, a-Si, n+ a-Si	
Coat photoresist		n+ a-si	
Expose			
Develop	PVD		
Clean			
Bake			
Etch island	Plasma etcher		CF_4; O_2; Cl_2
Strip			
Clean			
Inspect			

Process Step	Equipment	Product Materials	Ancillary Materials
Deposit gate electrode	CVD ·	Al, Al+barrier, Al+metal, or Al alloy	
Deposit pixel electrode	CVD	Al, Al+barrier, Al+metal, or Al alloy	
Deposit common electrode	CVD	Mo, Ta, MoTa, MoW, Al/Cr, or Ti/Al/Ti	
Coat photoresist	Coater		
Bake	Oven		
Expose	Stepper		
Develop	Developer		
Clean	Spin rinse dryer		
Bake	Oven		
Etch metal(s)	Wet bench		Al etch: $C1_2$+$BC1_3$/$C1_2$
			Al+barrier: Cl_2; BCl_3; N_2; CF_4
			Al+metal: Cl_2; BCl_3; N_2; CF_4
			Al alloy (Zr, Cu, Nd, Y): Cl_2; BCl_3; N_2; CF_4
			Ti: Cl_2; CF_4
			Mo: Cl_2; O_2; SF_6
			Cr: Cl_2; O_2
			W: Cl_2; O_2; SF_6
			MoTa: Cl_2; O_2; SF_6
Clean	Spin rinse dryer		
Strip	Developer		
Clean	Spin rinse dryer		
Deposit alignment layer	Roll coater	Polyimide, 500 to 1000 A	
Bake	Oven		
Rub	Rubbing machine		
Electrostatic discharge	Spin rinse dryer		Water
Test			

Display Cell Assembly

Process Step	Equipment	Process material/chemical	Notes
Apply seal	Screen printer	Epoxy resin, acrylic resin, etc.	
Cure	Oven		
Apply spacers	Spacer sprayer	Divinylbenzene-type resin or silica	
Inspection	Microscope		
Align and assemble plates			Each glass plate 1.1 mm thick
Cure	Oven		
Scribe and break			400 different types exist; more than one used
Inject liquid crystal	Vacuum/injection system	Polycyclic aromatic/halogenated hydrocarbon; cyanobiphenyl; phenylcyclohexane compound	0.8 mg/cm^2
Seal		Epoxy resin, acrylic resin, etc.	Sealing LC-injection hole
Cure	UV light source/oven		
Clean			
Attach front polarizer	Laminator	Polyvinyl alcohol-iodine	.2 - .3 mm cellulose triacetate; cellulose acetate butyrate-protective layer
Attach rear polarizer	Laminator	Polyvinyl alcohol-iodine	.2 - .3 mm cellulose triacetate; cellulose acetate butyrate-protective layer
Clean			
Inspect/test display			

Display Module Assembly

Process Step	Process material/chemical	Notes
Attach row drivers	PWB, TAB (polyimide film, sealing resin)	
Attach column drivers	TAB (polyimide film, sealing resin)	
Attach backlight	Glass fluorescent material, 20ppm Hg (notebook computer)	
Inspect		
Clean circuit boards		
Test		
Attach controller	TAB (polyimide film, sealing resin)	
Attach passive components		
Attach packaging hardware		
Attach interconnects		
Test unit		

Appendix E

Cannon FPD: Detailed Bill of Materials

Cannon FLCD 15C01

Glossary

a:Si	Amorphous silicon
Active center	Location of the unpaired electron on a free radical, where reactions take place.
Alignment layer	A layer and/or surface treatment applied to the boundary of a liquid crystal cell to induce a particular director orientation. For example, a layer of polyimide buffed in one direction induces alignment parallel to the buffing direction, or a surfactant may be polymerized on a boundary surface to induce perpendicular alignment.
AMLCD	Active-matrix liquid crystal display
Amorphous	Irregular; having no discernible order or shape. In the context of solids, the molecules are randomly arranged, as in glass, rather than periodically arranged, as in a crystalline material.
Amorphous polymers	A glass-like structure with tangled chains and no long-range order.
Amphiphilic	A molecule with a hydrophilic head and a hydrophobic tail (i.e., a molecule that has one end that attracts water and one end that repels water).
Anisotropic	Having properties that vary depending on the direction of measurement. In liquid crystals, this is due to the alignment and the shape of the molecules. Dielectric anisotropy means different dielectric strengths along different axes, and refractive anisotropy means different refractive indices along different axes.
APCVD	Atmospheric pressure chemical vapor deposition
Aquadag	An aqueous conductive coating found on the faceplate.
Backbone	The main structure of a polymer onto which substituents are attached.
Biaxial	Possesses two directions along which monochromatic light vibrating in any plane will travel with the same velocity.
Birefringence	Also called double refraction. The property of uniaxial anisotropic materials in which light propagates at different velocities, depending on its direction of polarization relative to the optic axis.
Block polymers	Polymers composed of two or more connected sequences (blocks) of homopolymers.
BOM	Bill of materials
Buffing	To give the inner glass surfaces of a liquid crystal cell a texture, in order to align the liquid crystal molecules in a certain direction parallel to the surfaces.
CCFT	Cold cathode fluorescent tube
Chain polymer	A polymer in which the repetition of units is linear. The

	monomers are linked end to end, forming a single straight polymer.
Chiral Nematic	Similar to the nematic phase; however, in the cholesteric phase, molecules in the different layers orient at a slight angle relative to each other (rather than parallel, as in the nematic). Each consecutive molecule is rotated slightly relative to the one before it. Therefore, instead of the constant director of the nematic, the cholesteric director rotates helically throughout the sample.
COB	Chip-on-board
COF	Chip-on-film
COG	Chip-on-glass
Convergence	The ability of an electron beam to hit the correct phosphor dot.
Cross-linking	A process in which bonds are formed joining adjacent molecules. At low density, these bonds add to the elasticity of the polymer. At higher densities, they eventually produce rigidity in the polymers.
CRT	Cathode ray tube. A glass vacuum tube used in televisions and monitors.
Cullet	Broken glass from CRT
CVD	Chemical vapor deposition
DfE Program	EPA's Design for the Environment Program
Dielectric	A material that is inserted between the plates of a capacitor to increase its effective capacitance.
Dot pitch	The vertical distance between the centers of adjacent pixels. Dot pitch is an important determinant in the clarity of a color monitor.
E/S	Etch stop
EOL	End-of-life
FPD	Flat panel display
Frit	Solder glass made of lead oxide, zinc oxide, and boron oxide, mixed with nitrocellulose binder and amyl acetate to form a paste.
Gate	Control terminal of a thin-film-transistor.
Grille dag	A coating of contrast-enhancing material applied to the faceplate.
IC	Integrated circuit
IPS	In-plane switching
Isotropic	Disordered and without any preferred direction.
ITO	Indium tin oxide
LCD	Liquid crystal display
Liquid crystal	A thermodynamic stable phase characterized by anisotropy of properties without the existence of a three-dimensional crystal lattice, generally lying in the temperature range between the solid and isotropic liquid phase.

Mesomorphic substance	Another term for a liquid crystal material.
MIM	Metal-insulator metal
Monochromatic light	Light composed of only one specific wavelength.
Nematic	Liquid crystals are characterized by long-range orientational order and the random disposition of the centers of gravity in individual molecules. Nematics may be characterized as the simplest spontaneously anisotropic liquids.
NMP	N-methyl pyrrolidinone
OEM	Original equipment manufacturer
p:Si	Polycrystalline silicon
Passivation	A thin-film protective layer that is applied to a glass substrate prior to LCD fabrication. It makes the surface "passive" in that no ions can migrate from the glass to the silicon film.
PECVD	Plasma-enhanced chemical vapor deposition
Phosphors	Luminescent materials
Photoresist	A photosensitive polyimide resin
PMLCD	Passive matrix liquid crystal display
Polyimide	A cyclopolymerized organic material capable of withstanding high temperatures (at least 300°C).
Polymer liquid crystals	Polymers that contain mesogen units and thus have liquid crystal properties.
PVD	Physical vapor deposition
PWB	Printed wiring board
Slurry	A thin paste that has solids suspended in liquids.
STN	Super-twisted nematic, a passive-matrix LCD technology
TAB	Tab automated bonding
TFT-LCD	Thin film transistor liquid crystal display
TMAH	Trimethylamine hydrochloride

Displays

The display screen is one of the most critical, and most volume-intensive, components of computer systems. The predominant display technology is the cathode ray tube (CRT), which provides a rich, high-resolution display well-suited to a wide range of user requirements. Advances in new display technologies are helping to position flat panel displays (FPDs) as viable alternatives to CRTs, particularly in applications where size, weight, or portability are concerns.

The CRT is the display of choice for both television and computer displays while other technologies (vacuum fluorescent, plasma panels, and electroluminescent panels) find significant use in industrial and instrumentation applications.

This chapter is divided into two sections--CRTs and FPDs. Each section discusses the strength of the market and the environmental issues for these two types of displays.

Background of CRTs

Markets

In the U.S., CRTs are produced primarily for the color-television industry and the monochrome industrial, military, and computer industries. Television dominates the installed display base, both in terms of size (the 19- to 27-inch viewing diagonal TVs dominate the marketplace) and ubiquity (saturation reached 98% of all households by 1988). Computer displays are also becoming pervasive with sales exceeding 8.8 million (one-third as large as the television market) in 1992. The industrial market and the instrumentation market (i.e., medical displays, automotive, appliance displays) number in the tens of millions of displays per year, but do not constitute an equivalent environmental impact because of their smaller size.

Although the color computer display industry is dominated by imports with negligible manufacturing in the U.S., the Electronic Industries Association (EIA) reports that color television CRT manufacturing in the U.S. grew by 43% from 1986 to 1992, while monochrome CRT manufacturing fell 84% (see Table 7-1).

Year	1986	1988	1990	1992
Color CRTs	11684	13747	14600	16741
Mono CRTs	3959	2580	1411	633

Table 7-1. Sales reported by EIA manufacturing companies (unit: thousands).

The market for CRTs will parallel the strong growth in the production of consumer and industrial electronics, particularly if the NAFTA agreement creates an advantage for CRTs manufactured in North America. TVs, computers, oscilloscopes, and other testing and measuring devices will continue to be a strong market, although future development of multimedia entertainment systems and high-definition television is also expected to drive the market for CRTs (see Tables 7-2 and 7-3).

Year	1989	1990	1991	1992
Units	15,055.6	14,653.8	14,979.0	16,803.3
Dollars	1,510,844	1,552,463	1,541,258	1,704,056

Table 7-2. U.S. factory sales (thousands of units and dollars).[35]

Year	1988	1989	1990	1991	1992
Imports	122.2	274.0	239.9	264	303.3
Exports	79.2	103.2	86.2	143.6	161.4

Table 7-3. Trade trends of CRTs in the U.S.($ millions).

The worldwide market for CRTs used in both consumer television and non-consumer equipment reached 168 million units valued at $13.6 billion in 1993.[36] The market is estimated to grow to 223 million units valued at $21 billion by the year 2000. The non-consumer segment, which includes computers and industrial equipment, represented 27% of the units and 34% of the value in 1993--these ratios are not expected to change by more than 1% over the forecast period.

The CRT continues to be the predominant display device because of its low cost per pixel and high-quality display. Although flat-panel technologies are beginning to make their presence known in the marketplace, their share of the computer monitor market will still be approximately 30% of the total by the year 2000 (see Table 7-4).

Year	CRT	LCD	Other FPD
1993	11	2	0.1
1994	13	4	0.1
1995	15	5	0.1
1996	17	6	0.1
1997	18	7	0.1
1998	19	8	0.1
1999	19	9	0.2
2000	20	9	0.2

Table 7-4. Worldwide market for CRT and flat panel displays (FPDs) in computer equipment ($ billions).[37]

Technology of CRTs

A CRT uses high voltages to accelerate electrons toward a luminescent material called a "phosphor" that is deposited on the faceplate. The phosphor converts the kinetic energy of the electrons into light. In a monochrome CRT, the electrons are returned to the high voltage power supply via an aluminized film that connects the phosphor to the anode button. This film also increases efficiency of the CRT by directing all the light toward the observer. In a color CRT, the phosphors are patterned in dots or stripes of red, green, and blue phosphors. The electrons are emitted from three cathodes in the electron gun assembly and pass through an apertured metal "shadow mask" during their passage to the phosphor. Electrons from each cathode that are directed at the wrong color phosphor are absorbed by the shadow mask. This color selection method relying on three spatially separated sources and a shadow mask is described as the "parallax color selection method."

Parallax color selection permits the brightness of each color to be controlled by modulating the current of the electron beam emanating from the appropriate cathode. Pictures are created by first focusing the electron beams into tiny spots, which are moved by deflecting the electron beams electromagnetically so that the spots move across the phosphor surface in a left-to-right and top-to-bottom raster. This system is extremely efficient in that it only requires three video drivers and connections instead of the 2000 or so in the most common flat panel display.

The electron guns require high vacuum to achieve long life and the bulb envelope must have sound mechanical integrity to resist the force of atmospheric pressure. The high voltages used to accelerate the electrons must be insulated from the external surfaces of the tube and the envelope must have excellent electrical insulating properties. The decelerating electrons produce X-rays and the envelope must also be a good X-ray absorber.

Structure

The CRT display is composed of a glass panel, a cathode ray tube, a casing, various connectors, wiring, shielding, and a deflection yoke. The tube ranges in weight from 40 to 70 pounds. Primary issues associated with the CRT display, other than its bulk, center around environmental and safety concerns. The end-of-life disposal of the unit is problematic due to the limited cost-effective disposal options for leaded glass, mixed plastics, and other components of the display. The poor quality of recycled CRT glass and lack of markets further complicate disposition alternatives.

It should be noted that the three types of CRTs (color, direct view monochrome, and projection monochrome) are different in their manufacture and envelope composition. The internal shadow mask of the color CRT requires an envelope that can be opened for deposition of the patterned phosphor screen, the contrast enhancement material (graphite), the reflective aluminum with its lacquer leveling layer, and the aquadag (graphite and silicate conductive coating). The two halves of the envelope are mated with the shadow mask and sealed together with a low temperature frit (a solder glass with organic binders) in a high temperature bake process called Lehr bake. The monochrome tubes for direct view or projection can be made from one-piece bulbs without resorting to the frit glass seal.

Projection displays introduce additional components that have their own post-consumer implications. These include the lenses, CRT mounts, ethylene glycol cooling liquid, glass and plastic mirrors, and plastic projection screens, as well as significantly larger cabinets. However, the mass of the three monochrome projection CRTs is considerable less than that of a comparable direct view CRT.

Key Environmental Issues and Stakeholders

Although there are several issues of environmental concern in the manufacture of CRT displays, the primary issues concern disposal of end-of-life CRTs and the use of lead in the components. The lead content of the CRT is predominantly confined to the funnel of the CRT. The industry uses both a no-lead and a 2% to 3% lead faceplate composition with a trend toward increasing the use of the no-lead composition. Approximate lead content is shown in Table 7-5.

The control of dusts, wash water, etching solutions, and the careful disposal of industrial waste has made the industrial workplace environmentally conscious. During use, the CRT glass does not release lead. Thus, industry has identified post-consumer disposal as the key environmental issue, with lead leaching from the CRT envelope the primary environmental concern.

Glass	Lead Content
Panel	2% to 3% (No-lead compositions were introduced in the past decade)
Funnel	24%
Neck	30%
Frit	70%

Table 7-5. Percentage of lead in glass used in TVs.

Because the CRT contains lead (primarily in the funnel, neck, and frit), the disposal of the display falls under the control of the "Land Disposal Ban Program" of the Resource Conservation and Recovery Act (RCRA), Class C materials. Thus, in order to landfill the CRT display in accordance with EPA regulations, it must first be dismantled, crushed, and micro-encapsulated. However, the lead in the glass is embedded in the glass matrix and is therefore stable and immobile. Release of the lead from the CRT display is directly proportional to the amount of surface area exposed. The surface area of the glass is greatly increased when the cullet (pieces of discarded glass used with new materials to create glass) is pre-treated in the manner that the EPA requires for disposal (since crushing increases surface area), and therefore the potential level of leaching is likely to increase. Grinding the cullet also produces a lead-containing dust.

Cement encapsulation of the crushed CRT is the required method, but it has been postulated that cement actually disintegrates much more quickly than glass, releasing the lead sooner than if it had remained in the glass alone. Furthermore, the EPA requirements for the disposal of CRTs involve a complex process that has overburdened the producers, the disposal facilities, and the EPA with requirements, paperwork, and has also reduced the number of available disposal facilities. The CRT industry believes that there are better disposal practices than the EPA-recommended microencapsulation disposal method.

Glass Recycling

It is certain that attaining 100% productive use of post-consumer CRT glass will require the development of new recycling strategies, including resmelting and downcycling (finding new users and markets).

The existing processing methods that conform with EPA regulations are costly, prompting manufacturers to consider recycling as an alternative to encapsulation. However, adequate technology for the cost-effective recycling of broken CRT glass by the manufacturer does not exist and the separation of component materials is a major challenge. Because so many of the various parts of the display contain glass of different sorts, different contaminants, and different chemicals, their mixtures are rarely pure and are often unusable. While most large CRTs consumed in North America are manufactured domestically, almost all of the computer monitor CRTs are imported, creating a source of recycled glass that is foreign to the North American manufacturing process. There are few alternative materials being used, and even fewer uses for reprocessed materials, which returns the manufacturer to the disposal dilemma once again. In order to resolve the problems of recycling, there are several issues that should be addressed:[38]

- Simplification of mechanical disassembly.
- Avoiding self-contaminating combinations of materials.
- Standardization of component materials.
- Physical separation of high metal content items.

During the EPA Region I conference on Reduction of Heavy Metals in Municipal Solid Waste, several approaches to reduced introduction of lead from CRTs into the environment were presented. The primary approaches identified were recycling and downcycling to permit the continuing beneficial use of lead without creating any environmental impact. Also mentioned were the trend to use no-lead panels and the search for alternative lead free materials. Due to the high conversion and running costs for converting the 700-ton panel glass facilities, 100% use of no-lead glass will probably not be economically viable for many years. Corning estimates a running cost increase of about 6% for such a material substitution in their process.

The first recycling strategy is to use old CRT glass as a raw material for new CRT glass. This approach is limited by the shifting composition of glass over time and by the extreme risk of contaminating a large batch of glass. When the value of glass is about $1 per pound, a 700-ton tank load of glass spoiled by contamination represents over $1 million in wasted material and days of idle production capacity while the tank is cleaned and refilled. With JIT (just in time) manufacturing, no danger of tank upset is acceptable and the high dollar risk reduces the value of glass in the recycling stream. The recycling of broken CRT glass is being done by Dunkirk International Glass and Ceramic, who cleans and sorts the cullet by composition for return to the Thomson Consumer Electronics and Techneglas glass plants.

The second recycling strategy, practiced by Sony, is to return the whole tube to primary lead smelters as an ore for lead refining. The resulting materials are pure and highly salable as feed stock for the lead industries. The obvious drawback is that smelting must be followed by other processes before the materials become glass and the total processing cost may be higher than direct recycling. In any event, broken, mixed and dirty glass can be smelted rather than risking contamination of the glass making process.

Case Study: Sony USA Initiative for CRT Glass Recycling[39]

Because scrap cathode ray tube glass is regulated as hazardous waste when disposed, Sony Engineering and Manufacturing of America (SEMA) developed procedures to reduce waste in their CRT manufacturing operation and reuse the remaining material in a beneficial way. To accomplish this objective, the company used a multifaceted approach.

The first step involved waste minimization. By controlling the handling and shipment of lead glass, the company could drastically reduce the amount of waste it produced in breakage during production, shipping, and handling. By using training, process changes, attitude changes, and employee involvement, the company began reducing the amount of waste generated.

The second step involved the initiation of an agreement between the company and its glass suppliers, which enabled the return of clean glass from Sony to be reused as cullet by the supplier. Because a single impurity in a 1,000,000 pound vat of molten glass can render the whole batch useless, trust had to be developed over time between the company and the supplier before they would allow the interchange of used glass.

After 63.5% of the waste stream was eliminated through minimization efforts, and 23.5% was removed through the recycling of cullet, the third step focused on the remaining 13% of the waste stream. The remaining percentage was classified as mixed, broken, and dirty glass. This remaining waste was utilized by running it through a smelting process, using the glass waste as a replacement for silica. This smelting process removes any lead or other heavy metals from produced glass, and, in effect, "cleans" the glass. Also, since the waste glass had been used in a beneficial way as a "substitute for a commercial process without first being reclaimed" it becomes an exemption to the "regulated solid waste" classification of RCRA, and can subsequently be disposed. By using these processes, SEMA is able to recover 100% of their lead glass waste stream and reduce glass that once would have been extremely expensive to dispose of in the traditional manner.

Stakeholders

Identification of specific stakeholders in this process provides a basis for proposing industry alliances to address these challenges. Companies manufacturing CRTs in the U.S. include Zenith Electronics, Clinton Electronics, Thomas Electronics, Raytheon, Tektronix, Imaging and Sensing Technology, and Hughes Display Devices. Foreign companies with CRT manufacturing in the U.S. include Philips, Thomson, Matsushita, Toshiba, Sony, and Hitachi. Mitsubishi manufactures in Canada and several other companies are evaluating CRT manufacture installations in Mexico.

The industry is supported by three glass companies: Corning Asahi Video Products, Techneglas, and Thomson's Circleville, OH plant. In addition, glass is imported from Asahi, NEG, Samsung Corning, Schott, Philips, China, and the former Soviet Union. It is supported by the U.S. shadow mask manufacturer Buckbee Mears and by imports from Dai Nippon Printing, Dai Nippon Screening, and other foreign CRT manufacturers' integrated shadow mask facilities. Phosphors are supplied internally from vertically integrated manufacturing facilities and also by foreign manufacturers. The electron guns are made from precision metal parts manufactured by Premium Allied Tube and others fused into assemblies using low expansion coefficient electrical glasses made by Corning Asahi Video Products and Techneglas.

Energy Consumption and Waste Management Costs

Another environmental issue is the energy consumption of the display itself. The public, the Administration, and the federal government are beginning to realize the importance of introducing components that use only fractions of the energy once consumed by the electronics industry, both during the manufacturing process and during later consumer use. Enactment of the Energy Star Program (see Chapter 9) and an Executive Order, which directs federal agencies to procure only Energy Star computers, acts as a huge incentive for the development of energy-conscious designs.

The Department of Commerce data for energy consumption and pollution abatement costs do not specifically give data for CRT and flat panel display manufacturing. It is nevertheless useful to look at the data reported for the 4-digit SIC codes that include these industries. Available SIC codes include: electron tubes (SIC 3671), semiconductor and related devices (SIC 3674), and electronic components (SIC 3679).[40]

Tables 7-6 through 7-8 give some idea of the energy consumption and pollution abatement costs and expenditures for the 4-digit SIC codes, which include the 5 and 7 digit SIC codes that specifically cover the CRT, flat panel, and LCD manufacturing sectors.

SIC Code	Industry Group	Cost of Purchased Fuels and Electric Energy ($M)	Electric Energy Purchased		Cost of Purchased Fuels ($M)
			Quantity (Million kWh)	Cost ($M)	
3671	Electron tubes	58.8	881.0	45.5	13.3
3674	Semiconductors and related devices	467.3	7487.0	420.7	46.6
3679	Electronic components, n.e.c.[41]	186.6	2592.9	158.6	28.0

Table 7-6. Purchased fuels and electric energy used for 1991.[42]

SIC Code	Industry	Total PACE	Air	Water	Solid Waste
3671	Electron tubes	2.0	(D)[43]	(D)	(Z)[44]
3674	Semiconductors and related devices	49.8	28.7	17.6	2.9

3679	Electronic components, n.e.c.	5.6	0.9	2.9	1.8

Table 7-7. 1992 pollution abatement capital expenditures in millions of dollars.[45]

SIC Code	Industry	PAOC Total	PAOC Air	PAOC Water	PAOC Solid Waste	Cost Offsets Total	Cost Offsets Air	Cost Offsets Water	Cost Offsets Solid Waste
3671	Electron tubes	14.0	0.7	5.5	7.8	(D)	(Z)	(D)	(D)
3674	Semiconductors and related devices	132.7	33.0	65.1	34.5	12.4	0.3	0.7	11.4
3679	Electronic components, n.e.c.	51.0	11.6	20.5	18.9	2.3	0.1	0.8	1.4

Table 7-8. 1993 pollution abatement operating costs (PAOC) and cost offsets for 1992[46] in millions of dollars. Cost offsets are pollution abatement costs that are recovered through the reuse or sale of recovered materials and energy.

Priority Needs Matrix

Priority Need (decreasing order of priority)	Approach	Selected Tasks
* Establish infrastructure for post-consumer disposition of CRT glass.	* Survey and assess usability of existing systems for post-consumer disposition.	* Educate municipal waste handlers in proper CRT handling procedures. * Study infrastructure requirements of disposition strategies.
* Reduce lead in CRTs.	* Look for alternative glass materials that meet the same safety/cost standards.	* Develop new frit, face plate and funnel compositions.
* Promote alternative uses for post-consumer CRT glass.	* Look for and/or establish alternative markets.	* Catalog existing uses. * Research new uses.
* Increase processability of post-consumer CRT glass.	* Establish industry-wide acceptance of a single glass composition. * Develop processes for separating and cleaning broken, dirty glass.	* Develop a single glass composition that meets industry needs. * Investigate new bulb cutting techniques. * Develop rapid statistical assay methods.

Discussion of the Matrix

Alternative Materials:

The glass companies are developing lead-free frits, which may not be practical because of cost or performance considerations. Similarly, previous attempts to reduce the thickness of the funnel (required if the lead content is reduced) causes the bulb design process to fail because it lacks the proper implosion safety performance. Both of these technical problems should be placed with the national labs for evaluation from a new perspective.

Reduce Bioavailable Lead from CRTs:

The current EPA-recommended disposal practice needs to be reevaluated and alternative practices approved for use and introduced.

Separation and Cleaning of Post-Consumer CRTs and TV Glass:

The current method of separation is by scribing and thermal shocking to separate the CRT envelope into a panel and a funnel with a minimum of panel glass attached. Development of alternative separation methods (i.e., hydrocutting, sawing, laser assisted cracking) could increase both the percentage of materials that are recycled and ease of the recycling process. Contamination makes the recovered material worthless and cleaning methods must be developed to eliminate all risk of contamination. The companies currently involved in processing CRTs should be funded to explore processes they would not develop on their own.

Not all of the glass will be returned in complete bulbs with known history, composition, and easily separated materials. Much of the glass will be broken and dirty glass from unknown manufacturing periods and will have unknown (obsolete) composition. This glass represents the greatest challenge since it must be economically segregated into clean streams of a compatible composition glasses. New low cost separation methods will be necessary. Corning has recommended that Sandia Labs evaluate techniques such as heavy liquid, gravimetric separation techniques. Currently, UV and X-ray fluorescence technologies are being developed by DIGC for identifying the glasses being manufactured in 1994. Extension of these principles to automated sorting by applying machine vision and fuzzy logic will be a challenging technology development.

Recycled glass must be combined into large lots of known composition in order to make it valuable to the glass companies. Techniques for batch mixing and rapid assay of the resulting aggregate are not available and must be developed.

Downcycling Alternatives:

Downcycling of the glass content requires formulating glass with other inexpensive materials to create useful glass and/or useful forms for the secondary uses of the glass. Acceleration of a downcycling industry requires identification of products (radiation shielding, optical glass beads, shot peening beads, etc.), experimental melting to demonstrate the manufacturing process, and evaluation of the samples by the ultimate customer.

The typical engineer today may not be sufficiently prepared to incorporate design for environment. The number of material choices is overwhelming and the information on materials is often contradictory or unavailable. It is anticipated that these tools will be implemented as they become mature. The challenge remains supporting tool development.

Lawrence Livermore National Laboratory has done significant research in developing *in situ* heavy metal sensors. These should be made available to create environmentally sound manufacturing and recycling facilities which maximize the efficiency of recycling, protect workers from exposure to hazardous materials and prevent contamination of the environment. Compact chemical, spectroscopic, and piezoelectric sensors are ideal to track materials in liquid phase, gas phase and as particulate. ARPA should fund demonstration programs to evaluate these *in situ* sensors in industrial applications.

Regulatory Revision:

Current regulations effectively prevent experiments by imposing unnecessary permitting requirements. These come about when new chemicals appear in the exhaust stream from a factory and new permits would be required. Streamlining the permit practice to a basis of increased/decreased/experimental emissions of all types would speed reasonable experimental evaluations.

Further research is needed to refine the EPA risk assessment procedures in order to compare eventual environmental outcomes of disposal practices with respect to heavy metal bearing glasses. This work would allow recommendations for the safest disposal practices for post-consumer materials.

Background of Flat Panel Displays

Markets

FPDs are suitable for application in a wide range of markets--they may be used for applications traditionally using cathode ray tubes, or they may enable equipment manufacturers to develop products that use a flat panel's unique characteristics for a specific purpose, such as a laptop computer. Table 7-9 provides a list of FPD applications and indicates the scope of the market place for flat panel products.

Consumer	* Television * Games * Appliances
Transportation	* Automotive * Aircraft * Entertainment * Traffic control
Business	* Copiers/Fax * Tiled displays * Videophones * ATMs/vending machines
Industrial	* Lab/analytical * Process monitoring * X-ray security
Medical	* Lab equipment * Surgical assistance * Diagnostic imaging
Computers	* Desktop monitors * Portables displays * Personal digital assistants (PDAs)

Table 7-9. Flat panel display applications.

Worldwide sales of high-information content FPDs will continue to grow rapidly. Liquid crystal displays (LCDs) will dominate the market with a 75% market share. [This figure includes all types of LCDs, not just active matrix LCDs (AMLCDs)] Between 1993 and 1998, reduced AMLCD manufacturing problems will help sales reach $2.3 billion. Some estimates place the FPD market in 2003 at $13 billion--when AMLCDs will account for approximately 38% as other emissive technologies (e.g., electroluminescents, gas-plasma, field emission cathodes) achieve widespread commercialization.[47] Other sources estimate that the worldwide market for LCDs will be between $10 billion and $15.6 billion by 2000.[48]

The 1990s saw a huge increase in demand for portable products, thus increasing the demand for the FPDs. A once stagnant market became a boom, leaving the Japanese with a virtual monopoly on production. In 1994 the Administration announced its plan to award grants in excess of $600 million dollars to help stimulate active pursuit of flat panel display production in the U.S.[49] The first of these awards went to Optical Imaging Systems, the only U.S. manufacturer of active-matrix liquid crystal displays. Researchers believe that the introduction of these grants will stimulate development and help the U.S. corner at least 15% of the world FPD market.

FPD manufacturers worldwide offer a range of products for application in military, consumer, and industrial products. Flat panels offer tremendous advantages over cathode ray tubes for many products because FPDs can be designed to be thin, light-weight, and low power consumers. U.S. manufacturers offer a wide range of flat panel products and have been developing manufacturing capabilities to meet demand for FPDs.

Technology of FPDs

Many technologies exist to produce flat panel products including plasma display panels (PDPs), AMLCDs, field emission displays (FEDs), electroluminescent displays (ELs), vacuum fluorescent displays, light emitting diodes, and micromirrors. The Task Group is composed of representatives of the four major display technologies today--AMLCDs, PDPs, FEDs, and ELs. Each of theses technologies are described below and Table 7-10 summarizes their advantages and disadvantages.

Plasma Display Panels (PDPs):

PDPs are based on the plasma discharge that occurs when an ionized (usually noble) gas undergoes recombination. Electrons are removed from atoms to produce ions, later recombining with the ions and releasing energy in the form of light. A certain trigger (or priming) voltage is required to start the ionization process, after which the process will continue at a lower voltage, and the brightness of the emission will depend directly upon the current passing through the ionized gas, known as a plasma. The predominant technology is an AC driven display that obtains color by using the ultraviolet emission from a combination of He-Kr-Xe or Ne gases to excite red, green, and blue phosphors.

Electroluminescent Displays (ELs):

ELs are solid state devices with the active layer of manganese-doped zinc sulfide sandwiched between two insulators, which in turn is sandwiched between an indium-tin-oxide (ITO) column electrode and an aluminum row electrode. The phosphor layer (manganese-doped zinc sulfide) emits light when it is excited by the introduction of electrons between the row and column electrodes.

Field Emission Displays (FEDs):

Cold cathode field emission arrays contain a cathodoluminescent device that relies on extremely high field strengths at each element of an array of structured microscopic cathodes to relieve them of their electrons. The electrons then are accelerated to the anode where they strike a phosphor and produce light. No focusing structures are used, since the space between the cathode and phosphor/anode is extremely small.

Active Matrix Liquid Crystal Displays (AMLCDs):

AMLCDs are composed of a rear glass substrate patterned with thin-film transistors (TFTs), a front glass substrate with color filters, and a liquid crystal material filling the middle between the glass "sandwich." The array of thin-film transistors on the rear substrate is attached to electronic drivers that receive impulses from a computer chip attached to the host system. Each TFT acts as an on/off switch to activate a pixel, force the liquid crystal to twist, and allow light to pass through and form images on the display. Most AMLCDs use either an amorphous silicon or poly-silicon layer of semiconductor material within the TFT array. Metal layers and insulator layers are also patterned and deposited on the rear substrate.

Technology	Advantages	Disadvantages
Plasma Display Panel (PDP)	* Established technology * Wide viewing angle * Proven to be rugged and reliable * Multiple sources * Simplified driving circuit * Simple construction lends itself to low-cost, high volume production * Color is feasible * Long lifetime	* High-voltage driver requirements * Washout in bright sunlight * Low resolution
Electroluminescence (EL)	* Very thin and compact * High writing speed * Good readability and brightness * Gray-scale ability * Low-voltage operation * No catastrophic failure * Multi-color display available * High contrast ratio * Wide viewing angle * High volume manufacturing	* High voltage drivers required * Higher cost than standard LCD
Field Emission Displays (FEDs)	* Technology based on cathode luminescence (mature) Wide viewing angle * Potentially high luminous efficiency * Long history of phosphor development to draw from * High-speed addressing and response * No temperature sensitivity * Analog gray-scale and full color capability * Limited multilayer photolithography requirements * No filament to heat - no warm up time * Potentially scalable to large screen displays	* Efficient low-voltage phosphors not yet developed * Optimum manufacturing process not yet developed * High voltage drivers are required * Large area photolithography is required * High temperature fabrication equipment needed * Critical mass of participants not yet reached
Liquid Crystal Displays (LCD)	* Low driving voltage * Very thin display * Readable in direct sunlight * Available from many sources * Advanced technology	* High processing costs for active matrix types * Defect free TFT panels difficult to manufacture * High capital equipment investment for TFT-LCDs * Low transmissivity of color filters requires strong backlight * Polarizer set required

Table 7-10. Advantages and disadvantages of various display technologies.[50]

Key Environmental Issues and Stakeholders

Most U.S. display manufacturers are in research and development or start-up phases; thus, their focus is on technology development, deployment, and manufacturing capacity. Justifiably, business concerns such as raising capital and developing cost-competitive, viable products are the industry's primary objectives. In this early state of maturity, the flat panel industry will be hard pressed to initiate environmental management strategies beyond traditional pollution control or end-of-pipe solutions to waste management that meet permitting and other statutory-regulatory requirements. Nevertheless, efforts to consider environmental issues during the design stage of industrial development will pay off in the longer term.

Fortunately, many manufacturers may already be familiar with pollution prevention techniques, such as source reduction measures, that prevent waste or use less toxic materials. Companies that take advantage of such strategies may benefit from reduced materials costs, disposal costs, insurance costs, risk to workers and local communities, and improved corporate image. See Appendix B for a listing of environmental research initiatives underway at the National Laboratories.

The entire life cycle of the FPD product system must be addressed in order to accurately assess the environmental burden attributable to the FPDs. FPD producers should make every attempt to evaluate the total environmental burden associated with all phases of the product life cycle--the extraction of raw materials, the production of bulk and engineered materials, the manufacture of the product, use of the FPDs, disposal and retirement of the product. In addition, by considering the life cycle of the product, stakeholder analysis and competitive business issues that may affect flat panel manufacturers become evident.

Although FPDs offer several environmental advantages over cathode ray tubes--such as reduced weight-volume, energy consumption, and lead content--manufacturers can still make improvements in environmental performance in a number of areas, including manufacturing, use/service, and end-of-life management. (Note: a full life cycle analysis would consider earlier stages such as raw materials extraction and require quantitative data to accurately assess the environmental burden of each life cycle stage.)

Processes that are common among FPD manufacturers include photolithography, deposition, metallization, cleaning, sealing and encapsulation, clean room environments, and deionized water usage. The processes and materials used throughout the manufacture of FPDs that contribute environmental burdens include:

- Process chemicals throughout photolithography steps.
- Dopant and process gasses for deposition.
- Wet and dry etchants.
- Cleaning substances/techniques.
- Metallization processes.

Table 7-11 summarizes materials that are used commonly by FPD manufacturers. Quantitative data was not obtained and the information has been condensed to simplify the presentation of the results. This table illustrates that many of the materials/ processes and concerns in the manufacturing stage of FPD production are similar to that of integrated circuit manufacturing.

Manufacturing	Material Concern	Use/Service	End-of-Life
* Glass (e.g., Corning 7059 or soda lime glass) * Color Filters * Developers * Thinners * NMP/Acetone * Strippers * IPA * Acids (e.g., HCL, HNO_3, H_2SO_4, HF) * Ammonia * Adhesives * Indium Tin Oxide *	* Proper disposal and handling of materials. VOC, acid, and toxic emissions to ambient air or water * Proper treatment and handling. Impact on global warming and ozone depletion in the case of gases * Safe delivery and use. Impact on air quality * Particulate or waterborne emissions	* Power consumption over useful life of display (backlight and drivers) * Packaging	* Presence of heavy metals * Volume of displays (moldings, framing and display) * Interconnect and driver circuitry metals disposition * Reuse, recycle of TFTs, color

Etchants (e.g., acids and gases such as SF6, CF4, CL2, BCl3) * PECVD gases (e.g., Si3N4, PH3, NH3) * Metals (e.g., Al, Mo, Ta, Ti, Co) * TCE * Pump oil * Deionized water use and process cool water * Energy consumption (i.e., clean room and process equipment) * Chillers * Packaging	* Human toxicity * Proper recycling/reuse * Resource use/depletion * Impacts associated with fossil fuel combustion * Emission of refrigerant (CFC or HCFC) * Reduce volumes of waste--reuse or recycle	filters, or glass

Table 7-11. Key environmental issues over the product life cycle.

Beyond life cycle assessment, the FPD Task Group also recognizes the need to incorporate environmental requirements into the design of FPDs. Design approaches such as life cycle design (LCD) and Design for Environment (DFE) are state-of-the-art approaches for identifying and managing environmental issues over the product life cycle. These approaches enable manufacturers to reduce environmental burdens by changing the design of their products.

A number of companies have instituted proactive programs of pollution control, energy conservation, and resource conservation and are attempting to capitalize on pollution prevention opportunities. Three examples of these types of activities are provided here:

- An AMLCD manufacturer installed an acid neutralization system, a recirculating DI water system, and a combination of gas and oil chillers operated by an energy management software tool to conserve energy. The acid neutralization system was not required under permit conditions but was nevertheless installed at the facility. The DI water system and energy management plan were pursued because of the cost-saving opportunities.
- In response to a toxics use reduction program at the State level, a manufacturer of ELs created a source reduction committee that meets periodically to review pollution prevention options. To date, the committee has worked on eliminating CFCs, recycling solvents, and communicating with equipment manufacturers about tool designs that would improve environmental performance.
- At a manufacturing facility for FEDs, care is taken to select what is determined to be the most environmentally benign solvents. In addition, filtration processes, re-circulation systems, and shallower acid baths are used to reduce waste from the facility.

Stakeholders

Internal and external stakeholders must be considered throughout the product system supporting the manufacture, use, and end-of-life management of FPDs. Table 7-12 summarizes the varied stakeholders identified by the Task Group.

	External	Internal
Manufacture	* U.S. Display Consortium * OEMs * Equipment Suppliers * Material Suppliers * EPA/State Dept. of Env. Protection * U.S. Administration * Localities/State Economic Offices * Community Environmental Groups	* Management * Engineers * Facilities Staff * Designers * Marketing * Accounting * Purchasing * Environmental Professionals
Use/Service	* Consumers * OEMs * Government Agencies (e.g., FCC, FTC)	* Service Technicians
End-of-Life	* Waste Handlers * EPA/State Dept. of Env. Protection * Community Environmental Groups	

Table 7-12. Internal and external stakeholders to FPD industry.

Priority Issues and Needs

Priority environmental issues and needs in the FPD industry are, in many cases, directly related to technological advances made in the production process. Several priority issues relating to process improvement require attention to accomplish environmental objectives in the FPD industry.

- The U.S. Display Consortium (USDC), recognizing the importance of equipment and materials, issued requests for proposals in a number of areas including color filters, inspection and testing, dry etching, and proximity lithography. As these technologies are developed and semiconductor manufacturers leverage their know-how to support the FPD industry, the flat panel industry will significantly improve its manufacturing efficiency and environmental performance. Technologies that lead to higher material usage rates, higher yields, energy efficient clean rooms, and other process design advancements will result in significant improvements in environmental performance throughout the industry.
- Environmental performance improvements at the FPD manufacturing level are impacted by the ability of equipment manufacturers and material suppliers to develop more efficient and environmentally conscious tool designs and materials that are environmentally benign. FPD manufacturers must specify design requirements that consider key environmental issues, communicate these specifications to equipment and material suppliers, demand tools that meet these specifications, and test the processes so that the improved tools can be installed in full-scale manufacturing lines.
- Advancements in environmental performance also hinge upon how well manufacturers and suppliers of equipment and materials can identify product, process, distribution, and information management related issues that affect environmental performance. Product-related issues include all materials that go into the final product. Process-related issues include all materials and energy that are used to transform product components. Distribution-related issues include all packaging and transportation issues. Lastly, information management includes all of the data needed to monitor, track, and provide continuous feedback on product and process performance.
- FPD manufacturers need to focus on product design requirements that lead to environmentally conscious displays throughout the life of the product. First, screens must use glass that contains the least amount of harmful substances to human health and the environment. Designs must strive for the least weight, volume, sealants, and toxic heavy metals. Moreover, displays should operate at maximum energy efficiency and provide as high a luminous efficacy as possible. Potential user health concerns should be investigated. Lastly, reuse or recycling of displays needs to considered to avoid disposal.
- Process design considerations must be considered concurrently with product design specifications. Environmentally safe solvents, resists, color filters, and dopant gases should be used where feasible. Acid etchants, ozone depletors, and global warming substances need substitutes where feasible. In addition, energy efficient and water conservation measures must be implemented.
- On a regulatory level, FPD manufacturers must work more closely with government agencies to establish consistent classifications of facilities that are conducting similar operations. FPD industry representatives must work with government and environmental groups to educate these stakeholders on the processes used in production of displays as well as issues associated with other life cycle stages.

Issues and Activities Discussion

The FPD industry is faced with a number of challenges in terms of environmental improvement. Specifically: (1) what strategies will lead to reduction in pollution and are cost-effective and (2) which areas of manufacturing, use/service, or end-of-life management are environmental priorities? Human health and land use impacts occur in several categories, including:

- Energy consumption. * Ozone depletion.
- Resource use/depletion. * Water quality impacts.
- Global climate change. * Solid and hazardous waste.

The following section will briefly review each of the impact categories and describe efforts already underway within the industry to reduce environmental burdens.

Energy Consumption:

Energy use is one of the most important environmental issues facing FPD manufacturers and other semiconductor and electronics producers worldwide. Energy consumption at FPD manufacturing facilities is substantial in order to power the process equipment, clean room machinery, waste disposal equipment, and the facility's daily requirements for computers, lights, etc.

- Clean Room Design: Clean rooms are mechanically-intensive facilities that consume enormous amounts of electrical power.
- Chillers: Chillers cool the water and air conditioning systems for the facility. Both gas and oil powered chillers are used throughout the industry.
- Product Use Over Lifetime: Energy requirements over the lifetime of displays will also result in environmental impacts. Whether the products are powered by fossil fuel or battery power, the efficiency of its power use will impact the environment.

Resource Use/Depletion:

The primary resource of concern used in FPD manufacturing is water. Water is provided by public water systems for use in DI water systems and process equipment cooling. The rate of consumption of FPD manufacturers results in a huge demand for municipal water over the lifetime of the facility. The impact of this demand is relative to the area in which the facility is built and the capacity of local water systems to supply this rate of flow.

As described above, non-renewable energy is consumed throughout the production of FPDs due to the power requirements of clean rooms, process equipment, etc. The impact of this consumption includes the emission of CO2 and sulfur dioxide, and the impacts range from global warming to acid rain, affecting populations at local, regional, and global levels.

Global Climate Change:

Global warming gases such as carbon tetrafluoride or tetrafluormethane (CF4), hexafluorehane (C2F6), nitrogen trifluoride (NF3), sulfur hexafluoride (SF6), methane (CH4), C3F8 (Freon 38), and nitrous oxide (N2O) are used for a variety of purposes, including chemical vapor deposition, etching, and cleaning chambers. These chemicals have each been determined to have a Global Warming Potential (GWP) based on the atmospheric lifetime of a chemical and its infrared absorption spectrum relative to carbon dioxide. Table 7-13 presents the GWPs for a group of compounds including those listed above.

Ozone Depletion:

These compounds contribute to ozone depletion by releasing CFC molecules into the atmosphere. Cleaning operations have historically made use of harmful CFCs; however, most manufacturers have eliminated the use of these chemicals due to Clean Air Act and Montreal Protocol requirements. Facilities still emit ozone depletors (i.e., HCFCs) through industrial chillers used to produce air conditioning and process cool water.

Water Quality Impacts:

Water used on-site for the manufacture of FPDs is ultimately discharged into the publicly owned treatment works (POTW) or water bodies located near the facility. The effluent from the FPD facilities also includes neutralized acids and metals generally via treatment by a neutralization system. Effluent discharges are subject to POTW or Clean Water Act regulations.

Solid and Hazardous Waste:

Solid waste streams generated from FPD manufacturers include scrap glass and packaging materials. Hazardous waste resulting from the manufacture of FPDs include solvents used as cleaning agents, photoresist materials, and process solutions such as spent IPA. Manufacturers are responsible for storing the hazardous wastes and hiring permitted waste handlers to transport the material to either a registered disposal site or other acceptable use such as a chemical refinery. Waste streams may also be generated throughout manufacturing steps if displays are defective. In addition, after a display is retired by the consumer, its disposition in a landfill or other disposal site could result in environmental burdens.

Chemical	Lifetime (years)	GWP (100 years)
CF4	>50,000	10,900
C2F6	>10,000	11,500
NF3	<179	24,200
SF6	3,200	21,000
C3F8	>10,000	N/A

CO2	120	1
CH4	10.5	11
CFC-11	55	3400
CFC-12	116	7100
N2O	132	270

Table 7-13. Global warming potentials for industrial chemicals.[51]

Strategies for Reducing Environmental Impact and Risk

Manufacturers have numerous opportunities across the life cycle of a product to reduce environmental impact. The following lists examples of proven strategies:

- Product Life Extension
  - Extend useful life
  - Increase durability
  - Ensure adaptability
  - Increase reliability
  - Expand service options
  - Simplify maintenance
  - Facilitate reparability
  - Enable remanufacture of products
  - Accommodate reuse of product
- Material Life Extension
  - Develop recycling infrastructure
  - Examine recycling pathways
  - Use recyclable materials
- Material Selection
  - Use substitute materials
  - Devise reformulations
- Reduced Material Intensiveness
  - Conserve resources
- Process Management
  - Process substitution
  - Process energy efficiency
  - Process materials efficiency
  - Process control
  - Improved process layout
  - Inventory control and material handling
  - Facilities planning
  - Treatment and disposal
- Efficient Distribution
  - Optimize transportation systems
  - Reduce packaging
  - Use alternative packaging materials
- Improved Management Practices
  - Using office materials and equipment efficiently
  - Phase out high impact products
  - Choose environmentally responsible suppliers or contractors
  - Encourage labeling and advertise environmental claims

Priority Needs Matrix

Priority Need (decreasing order of priority)	Approach	Selected Tasks
* Determine the feasibility of	* Develop cost-effective recovery mechanisms. *	* Assess existing recovery systems. *

reusing display parts or components.	Assess disposal rates and volumes. * Assess consumer and technological trends affecting disposal.	Study consumer disposal trends and options. * Develop models to predict optimum component recovery.
* Institute processes to minimize hazardous materials use and releases.	* Evaluate containment and reuse/recovery systems for PFCs and certain glycol ethers. * Recovery of spent solvents. * Eliminate chemical glass-cleaning processes.	* Generate list of alternatives to glycol ethers and PFCs. * Install closed-loop materials recovery systems. * Determine areas for reducing hazardous materials use through risk management techniques.
* Strengthen relationship between FPD suppliers and manufacturers to focus on environmental needs.	* Establish FPD manufacturer/ supplier environmental design teams. * Increase environmental information flow on hazardous materials used.	* Establish joint task group with SEMI. * Establish a system for retrieving all chemical and materials data.
* Establish DFE practices for FPD manufacture.	* Promulgate DFE principles. * Provide DFE training.	* Develop DFE manufacturing guidebook. * Transfer technology and approaches from semiconductor industry, where appropriate.
* Optimize use/service performance.	* Decrease power consumption. * Extend useful life, durability and facilitate serviceability.	* Research manufacturing methods for more efficient displays.

Disposition

Introduction

Personal computers and other electronic products are becoming increasingly pervasive in our homes, workplaces, and schools. Each one of these products will eventually reach the end of its useful life, and will require disposition of one sort or another. The sheer number of electronic products currently in the marketplace has caught the attention of solid and hazardous waste policy makers, companies concerned with appropriate disposition, and business entrepreneurs who see value in the purported waste. In addition, technology improvements consistently result in less expensive, more powerful products, and thus may hasten the replacement and eventual disposition of electronic goods.

The concerns most frequently raised about electronic product disposal are their bulk, and the hazardous constituents some of them contain. In many parts of the U.S. and the world, landfill space (and the difficulty in siting new landfills even if space is available), is a sufficiently important concern to warrant close examination of the growing electronic component of the waste stream. In addition, electronic products carry the added burden of a variety of hazardous constituents, from lead solder to batteries. Ensuring appropriate disposition of such hazardous constituents is a challenging problem.

The economic opportunities inherent in the electronic waste stream have not gone unnoticed by business entrepreneurs and large companies. Unlike mechanical systems, electronic components do not "wear out." The cost of some new components is so high as to provide significant incentives to identify sources of used, less expensive components, especially in cascading uses. There is a healthy and growing independent secondary market for used computers and components, and many computer manufacturers are looking for ways to capture some of this market, and the value of their products, for a variety of their own uses.

Added to this mix of concern and opportunity is a very fluid regulatory situation, in which a few countries are starting to create models for controlling the disposition of electronics products. Companies are thus faced with a difficult array of influences which they must balance to address product disposition.

There are a number of different schemes which can be implemented, either through legislation or company action, that would address product disposition concerns. These include reverse distribution (product take-back), third-party product collection and disposition (public or private), outright disposal restrictions, and others. Reverse distribution schemes have received much attention, in part due to the German government's support for such a system. The German "electronic take-back" law has been circulated widely throughout the electronics industry, although it is not in effect in Germany at this time.

The complicated nature of a reverse distribution scheme makes it a vivid case study of the policy and logistical issues associated with any disposition scheme; therefore, the discussion below focuses on this option. However, it should be noted that it is only one of many choices available, and the relative lack of attention given to other options in industry and the government is itself an issue of concern. The discussion below highlights the myriad issues a company or policy maker must address when adopting any disposition system.

Product End-of-Life Management

There are four major issues that need to be taken into account before an infrastructure for a product end-of-life disposition industry can be established. First, some form of a product return system needs to be available and convenient to all customers. Two methods could achieve this: one approach would be to use existing dealer networks as customer return centers and store the old equipment until sufficient volumes require shipping to a recovery (recycling) center or original manufacturer. Another approach would be to develop a toll-free 1-800 number and contracts with various types of carriers for shipping discarded equipment.[52]

The second issue is determining who will pay for this service. One approach considered by industry is a discrete recycling fee charged to consumers at the time of purchase. In this way, the product user pays the cost of recycling and disposal. This differs from the current practice in most of Europe and the U.S., where product disposal is financed through municipal revenues and, therefore, distributed among all taxpayers.[53] The rate of technological advances makes it is very difficult to predict future recycling and recovery costs. Paying recycling costs at the time of product purchase presents a challenge to any industry that replaces "technically" obsolete products with new ones. Subsequently, product takeback offers from the manufacturers may be delayed.

The third issue is marketing these products. Since most returned products will be based upon outdated technology, critical service parts could be removed, certified, and then sold for use in some other industries (see Figure 8-1). Another approach is to sell the products for a lower price to customers who do not need leading-edge technology. Used products are often the most cost-effective source of replacement parts, particularly for discontinued products. With proper service and support, the used products often provide profitable opportunities to reuse equipment subassemblies, circuit boards, or components. Plastics and the metals that are recovered could be recycled for reuse or sold.

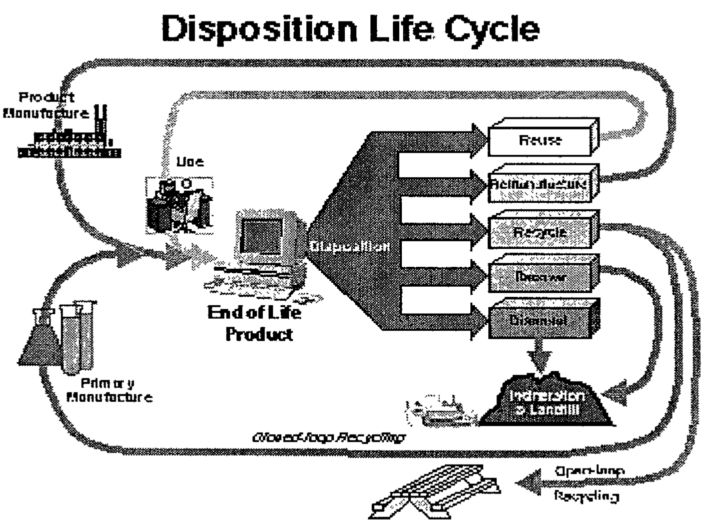

Figure 8-1. Disposition life cycle.[54]

The fourth issue is the calculation of the environmental burden of end-of-life options. It may be that certain options (e.g., recycling) are more burdensome to the environment than land disposal.

Disassembly and Recyclability Challenges

All manufactured products sooner or later develop defects, wear out, or simply become obsolete, thus becoming waste themselves--electronic products are no exception. Historically, the majority of these wastes made their way to landfills or incinerators. Groundwater contamination from leaking landfills, toxic emissions from incinerators, natural resource depletion, and disposal costs associated with diminishing landfill space, have brought "recycling" to the forefront of methods to address these issues.

One approach consists of voluntary and/or mandatory recycling programs at all governmental levels, worldwide. Moving away from a "throw-away" society will require the cooperation of everyone from the producers of products to the end-users. Product designers in particular have an important role to play since they can strive to design both toxic or other hazardous materials out of, and better recyclability into, products.

Product "takeback" and recycling laws, "eco-label" programs, and customer requirements impact the way we look at a product's end-of-life design considerations. For example, the German Blue-Angel program requires modular design to promote recyclability and also requires that producers takeback their old products from customers. As recycling becomes mandatory, the question of how to do it in an environmentally-friendly and cost-effective manner arises. The greater a product's recyclability, the more economical the extraction of the valuable materials that make up that product. Product recyclability can be enhanced through the judicious choice of materials and the incorporation of certain design features.

The trend toward increased recyclability in products has led to the concept of design for recyclability (DFR). Since the initial design of a product has been shown to lock in an estimated 80% to 90% of the product cost because of material and process selection, the most cost-effective place to address recyclability is in this initial design stage. Addressing the problem at the design stage is consistent with Total Quality Management (TQM) models. Recycling is recognized as a very effective resource management tool when materials can be recovered several times before they degrade and can no longer be reused. Recycling can be enhanced by:

- Ease of disassembly
- Material identification
- Simplification and parts consolidation
- Material selection and compatibility

In many cases disassembling and segregating various parts of the products increases the scrap value and promotes recycling--hence the similar need for design for disassembly (DFD) to maximize this value.

The typical individual product turnover rate in the electronics industry is so high that companies have developed highly sophisticated computer-aided design (CAD) tools to simplify and standardize the design process. The designers must not be burdened with the need to input or interpret the environmental impact data on which the analyses will be based, nor is there time to turn every designer into an environmental specialist. Rather, data on materials, as well as DFR and DFD considerations, should be incorporated into the CAD software so that the most appropriate choice is made automatically for the task at hand.

This automated process would use the existing design tools to access databases on environmental data, on environmental impact, on trade-off analyses, and on full life-cycle risks. These tools must be developed while keeping in mind that these are additional criteria the designers must incorporate into an already highly constrained solution space.

These tools will also allow for additional analyses to increase the recyclability of products including:

- Costs/savings for recycling versus disposal options.
- Review of ease/completeness of segregation.
- "What if" evaluations for different design options.

Policies and regulations associated with product takeback requirements promote the sharing of information between companies regarding the materials content of products and the disassembly instructions. These DFR and DFD tools and databases will provide the information necessary to meet government requirements for performing accurate life-cycle assessments. These tools will also support the efforts to move toward more modular designs that will enhance recyclability and improve the longevity of products.

A final area to be considered is the present state-of-art of the recycling industry. Most recycling operations consist of shredding products, some separation of materials, and the recycling of these materials for their raw material or energy value. This process results in the lowest recovery of the initial investment of the product, short of disposal. Modular design, DFD, and DFR can allow for the reuse of subassemblies, components, and housings, among other items, which can return a higher value than the inherent value of the item based on its materials composition.

Although the option always exists to recycle the raw materials from items that are no longer reusable, the alternatives may often be preferable (i.e., more cost-effective or profitable). However, the infrastructure and industries that are required to capture and reuse the higher value items are not yet in place. Therefore, design considerations will need to be made adaptable to keep pace with, as well as influence, the changing opportunities for enhanced reuse and recyclability.

Significant Materials used in Electronic Products

The three major materials used in the manufacture of electronic products are glass, metals, and plastics. The technical challenges of recovering these materials are discussed below.

Glass:

The electronics industry generates glass cullet for product applications such as color television picture tubes, color computer monitors, and monochromatic monitors. The CRT displays of television sets and computer monitors contain heavy metals, making the sets difficult to recycle. Glass constitutes about 50%, by weight, of the material in TV sets and represents a major recycling potential. Modern video displays contain at least six different glass elements, each with unique compositions and engineering requirements. In general, mixed glass is unsuitable for recycling. Although some CRT market share is moving to flat-panel screens, CRTs remain the predominant display technology. Issues of recycling CRTs are now coupled with those of flat-panel screens, which significantly reduce materials and energy usage, but pose environmental issues that are still being examined.

Metals:

Lead is the most common metal used in the electronics industry, primarily for CRT manufacturing and soldering. It is a toxic material that is strictly regulated by OSHA and the EPA. Although no cost-effective alternative for lead has yet been discovered, research is ongoing in several organizations to develop lead-free solder and glass alternatives. Concerns remain about the toxicity, long-term availability, and limitations of substitute materials such as conductive adhesives to replace lead and tin solder.

Plastics:

One of the problems with plastics recycling and recovery is the difficulty in getting high-quality material. While thermoplastic materials are recyclable, mixtures are unacceptable (15 to 20 types of plastics are used in producing a television set), so there is a need to reduce the variety of plastics used in specific products to a single material. Because of the incompatibility of various plastics, the parts disassembled from old products must be identified and sorted in order to separate different types of plastic. Current plastics-marking practices offer little help, as the type of additives, fillers, or flame retardant materials is not supplied.[55] Further studies are necessary to establish the most appropriate treatment for each type of plastic: recycle, regenerate, or incinerate.

Reverse distribution and product takeback initiatives could force manufacturers to consider environmentally-sound designs and disposal strategies for their products. Furthermore, these concepts also offer a closed-loop recycling system. More research should be conducted on this subject in order to derive an economically and environmentally feasible solution.

Equipment Collection Infrastructure

Voluntary asset recovery systems for electronic equipment are currently offered by many companies through warranty, repair, trade-in offers, and other return incentives. Some companies vertically integrate the collection, storage, repair/refurbishment, and/or shipment to recyclers, while others utilize third parties for any combination of these operations. Once disposed, components or scrap materials collected may eventually fall under the RCRA solid waste definition. Because no electronic equipment takeback mandate currently exists, except for batteries, these programs are instituted by the companies purely from a business stewardship perspective.

Some European disposition programs have seen the OEM as the responsible party for equipment collection and/or stewardship under mandatory takeback programs. Whether the program is instituted as a result of a government mandate or voluntarily by industry, it must ensure environmentally sound final disposition.

Building a cost-effective and responsible equipment collection infrastructure within municipal solid waste guidelines requires that several issues be addressed:

- Recycle Methods, Capacities, and Markets: Electronic equipment is currently being recycled using several methods, namely de-manufacturing and segregation into like materials for recycle/reuse; shred and post-shred into like materials for recycle; and refurbish and resell. Recyclers have the capacity to handle current volumes, but may not be able to absorb the added quantities resulting from mandated or organized product distribution programs. Also, markets need to grow at the same rate as recycling so storage does not become a problem.
- Business/Industry Electronic Equipment: Some end-of-life electronic equipment disposed of by business/industry may be regulated under RCRA. These entities must substantiate and verify the sound environmental final disposition of the equipment, incurring costs associated with managing materials classified as "hazardous."
- Consumer (household) Electronic Equipment: The objective is to remove end-of-life electronic equipment from municipal trash through reuse and recycling of material, thereby preventing its disposal in landfills or consumption in municipal incinerators. All household waste is currently exempt from regulation under RCRA. Municipal waste disposal prohibitions may require the development of collection, inventory, and transportation methods to accommodate equipment discarded by consumers.
- Municipal Curb-Side Pickup: One viable collection system is municipal curb-side pickup and subsequent shipment to recyclers. This will avoid having the OEMs develop parallel collection programs that will inevitably be financed by the consumer via initial product cost increases. Municipal management may result in an increase in local taxes to support the added burden if the scrap value is insufficient to cover management costs.

Potential deterrents to implementing voluntary product disposition initiatives include:

- Regulations, especially state-to-state variations, that inhibit, rather than encourage, environmentally sound programs.
- Defining end-of-life electronics products as "hazardous" and in need of close regulation--and, thus, having higher costs for handling--even if no firm evidence of hazardous effect exists.
- Federal and/or state regulation of consolidation points.
- The environmental costs (e.g., energy and waste).
- The financial costs.

Options for addressing voluntary asset recovery initiatives are as follows:

- The electronics industry, in conjunction with electronic product users, should form a working group to prepare a model program aimed at ensuring the environmentally sound stewardship of end-of-life electronic equipment.
- The electronics industry should lobby to have end-of-life electronic equipment exempted from the RCRA "solid waste" definition and, instead, identified as a raw material/commodity if it is being collected, stored, transported, and managed for recycle/recovery (this is being done by the IPC and the Electronic Industries Association).

Disassembly and Parts/Material Sorting

Traditional electronic products are not manufactured with a view towards after-use recycling. Although salvaging only a small portion from the available volumes of obsolete electronic scrap, most reclaim efforts currently focus on recovering selected components and valuable metals. Full service metal and component recycling requires a knowledge of resale values, recovery techniques, and environmentally sound metal purification and separation techniques. Available services offer combinations of manual, mechanical, chemical, and pyrometallurgical capabilities. Segregation, value, and volume all affect the net return. Until now, glass and plastic have largely been considered non-recyclables.

To facilitate disassembly and sorting of parts and materials, several key issues must be addressed:

- Increasing the recyclability of all components.
- Easing the disassembly and identification of component parts.
- Protecting OEM sensitive/confidential information.
- Encouraging OEMs to support creative applications for recycled products.
- Developing global and cross-industrial recommendations and initiatives--including parts and material reuse.

Potential deterrents for the disassembly and sorting of parts and materials are:

- Recycling, and/or the disposal of non-reusable materials in an environmentally correct manner, is expensive. This cost will continue to grow if the volume of non-recyclables is not reduced. Recycling must be profitable in order to succeed.
- OEMs must be willing to incorporate, and consumers must change their perception of, used parts (especially electronic components) in new products. Unless the quality and reliability issues associated with these parts are overcome, manufacturers will continue to pay the costs for new products (using virgin materials) plus face the probable future expense created by recycling and disposal regulations on obsolete products.

The following are recommended for implementing a disassembly and sorting procedure:

- Design for disassembly should include input from recyclers to assure ease of break-down, shipment, material segregation, and secondary market acceptance. Lower costs associated with time and effort will increase the likelihood of value in the secondary arena.
- Internationally accepted, generic codes on all components would allow instant scanning. This would alleviate the current difficulties associated with component/material identification, sorting, treatment, or recycling.
- Global education programs should offer a coordinated scheme for the benefits of recycling and reuse issues. Such programs could aid the marketing of products utilizing recycled parts and, equally important, help alleviate the public pressure for environmental policies that have too often been expensive, counter-productive, or unnecessary.

Part Refurbish/Remanufacture

At equipment end-of-life, many potentially reusable parts currently enter the waste stream. While in some cases material value is recovered, greater value can be realized if parts are reused for their originally intended function.

However, incorporating used parts back into new equipment requires highly reliable technologies to ensure that refurbished parts meet the same quality standards as new parts. This is especially important to dispel the current negative public belief surrounding used parts (and machines). Alternatively, parts that are not expected to meet the same performance standards as new ones can be redistributed in other products and markets. In this case, less rigorous standards may apply, thus permitting less extensive refurbishing and repair processes.

To facilitate parts reuse, the following major areas need to be addressed:

- Customer-vendor cooperation: Many parts contained in electronic equipment are purchased by equipment manufacturers from parts vendors. Electronic equipment manufacturers need to work cooperatively with the original part manufacturers to facilitate the reuse of parts. Parts manufacturers must design parts for refurbish/remanufacture and provide refurbish/remanufacture technical expertise. Equipment manufacturers need to specify used part requirements in purchasing contracts and provide the used parts for refurbish/remanufacture.
- Parts design for refurbish/remanufacture: Robustness needs to be designed into parts. Additionally, design should incorporate reparability. Potential failure sources should be identified up front and then designed out. Alternatively, the part can be designed for easy access and repair.
- Test procedures to ensure reliability and performance: Parts life needs to be established and demonstrated to a high confidence level. Reliability test procedures need to be developed to ensure that reused parts will meet the desired performance standards. These technologies should provide information on life expectancy and component aging characteristics.
- Technologies for tracking parts life and number of turnovers: Inexpensive means for tracking parts life and the number of turnovers can serve as a simple means for identifying parts that can potentially be reused. In some cases, reliability testing can provide enough data to predict expected reused part performance to an acceptable level of confidence. In these instances, parts life and the number of turnovers may be sufficient quality assurance information. This would reduce any costs associated with extensive performance testing.
- More environmentally acceptable cleaning technologies: Most refurbishing processes include at least one cleaning operation. Current technologies still rely heavily on cleaning solvents such as halogenated organics, and more recently, semi-aqueous and aqueous materials. More work needs to be conducted on alternative cleaning technologies such as carbon dioxide blasting and supercritical applications.

Potential deterrents to parts refurbishing and remanufacturing are:

- Procurement policies that specify new: While the federal government is attempting to incorporate environmental considerations into their procurement practices, many states continue to specify that office equipment be completely new. These contracts prohibit the use of reused parts.
- The belief of used as inferior: It is generally believed that all usedproducts are inferior to new ones. Education and awareness are important to dispel this perception and build customer confidence. Additionally, economic incentives could serve as a means for promoting purchase.

The following are recommended for implementing the use of refurbished and remanufactured parts in products:

- Incorporate the consideration for reused parts content into government and industry procurement practices: Frequently government practices set the stage for private organizations. In addition to considering used part content when purchasing their own office equipment, federal and state procurement offices can also require that their contractors and vendors adopt the same practice.
- Parts and equipment manufacturers need to work cooperatively: Cooperative efforts between part and equipment manufacturers would be most effective in maximizing part value. In addition to part design, standard test methods for evaluating used parts condition in terms of reliability and expected performance could be addressed.
- Develop parts reliability database: Part reliability data correlating life with performance could provide enough information on a specific part design to allow reuse without extensive testing. This effort would most logically be undertaken by parts and equipment manufacturers.
- Develop low-cost parts tracking technology: A rapid low cost means for determining the life status of a part could

be used in conjunction with the reliability database. This would provide a method for dismantlers to sort reusable parts from scrap.

- Develop more environmentally acceptable cleaning technologies: More development work needs to be conducted to make non-chemical cleaning technologies both technically and economically feasible. For example, while carbon dioxide cleaning technologies are being used in limited applications, economics currently present an obstacle to widespread use.

Recycling Technologies

Some materials--such as precious metals--have been recovered from electronic equipment for years because of their value. Others, such as ferrous metals, aluminum, stainless steel, glass, and plastics are just beginning to be recycled as the required technologies and infrastructures become available.

This section will focus primarily on plastics, because they are typically the most valuable materials in the electronics waste stream after the precious metals, and because they are being recycled in very limited amounts because of the technical and economic challenges. The economic challenges are mostly associated with the collection, disassembly, and market development issues. The technical challenges are just now beginning to be addressed.

The recycling of plastics from post-consumer packaging, particularly bottles, has become fairly well-established. While the engineered plastics typically found in electronic equipment streams have higher potential market values, their recovery and recycling present unique challenges compared to the recycling of plastics from shipping packaging. Some of these challenges include:

- A much greater number of different plastics, some with various types of fillers and additives that make their separation both more difficult and more important.
- More items constructed of multiple plastics.
- Opaque pigmentation and thick walls making polymer identification and sorting more difficult.
- Paint and metallic coatings on some plastics.
- Significant amounts of attached metallic items (e.g., labels).
- The abundance of other non-plastic items such as natural rubber, synthetic elastomers, and glass.
- Parts containing attached foam, fabric, or plastic films made of different materials.
- Larger (and more variable thickness) wall sections, increasing the challenges associated with efficient size reduction and control.

Some of the most important issues with regards to plastic recycling are:

- Plastics identification and sorting technology.
- Size reduction and liberation technology.
- Separation technology (for plastic and non-plastic foreign material).
- Paint and coatings removal.
- Upgrading.
- Re-use (particularly of older plastics containing flame retardants or other "undesirable" additives).
- Customer-added contamination such as labels and paints.
- Identification of post-consumer plastics that contain undesirable additives.

The two major potential "show stoppers" are getting the material back into a recyclable form economically and generating sustainable markets for it once it has been purified. Collection and dismantling of plastics from end-of-life electronic equipment is perhaps the most costly component, and must be addressed industry-wide to spread the capital and operational costs associated with such an undertaking. Individual company initiatives will likely be cost-prohibitive except in very targeted areas.

Market development is critical to making the activity economically viable. The revenue generated by the sale of the raw materials produced by the recycling activity must pay for that activity. The quality of the material will be one factor in determining its value. The development of adequate recycling technologies will help increase the quality of the product and reduce recycling costs.

Another factor in determining value is the supply of the raw material. Increased supplies will tend to decrease values and make the recycling activity less viable; therefore, finding high value markets for the recycled materials--preferably in closed-loop scenarios--is very important. The OEMs play a vital role in creating the demand for these materials by specifying recycled material content in new applications. Many OEMs still require 100% virgin materials while at the same time espousing recycling in response to perceived customer requirements.

In addition to technology breakthroughs, closed-loop and cross industrial application development for recycled materials needs to be conducted to increase the market for recycled materials.

The electronics industry should continue to work with the plastics industry, which is funding significant work in the area of technology development. It can also help ensure continued work in this area through its association with other groups, such as the National Center for Manufacturing Sciences (NCMS) and the National Institute of Standards and Technology (NIST), to encourage additional funding to these needed areas.

Material Science

The focus of materials science has been on developing new virgin materials for new uses. To facilitate product disposition, the focus must include material properties of used materials. How these materials can be used in products must be better understood.

To facilitate the re-use of materials, the following major areas need to be addressed:

- The basic properties of used materials need to be better understood. These properties are, in general, degraded in comparison with those of virgin materials. The effect on material properties of preparing for reprocessing (e.g., shredding) needs to be established in order to determine how materials can be reused. The effect of typical contaminants on the properties of materials for reuse also needs to be understood.
- Once the basic material properties of re-used materials are established, the technology of mixing various materials to come up with a final material with the desired properties needs to be developed. The goal is to develop the technology of mixing recycled materials to yield a final material with the properties of a virgin material.
- Processing technologies need to be optimized for recycled materials. This may require changing processing conditions to accommodate the different properties of recycled material.
- Better material separation technology needs to be developed to ensure streams of materials with less contamination for reuse.
- There needs to be an investigation of ways to increase the compatibility of materials so that materials can be reused without rigorous separation.

Potential deterrents to developing the field of materials science for reused materials are:

- If the costs associated with technology development and new equipment are too high, companies will be reluctant to invest in these areas.
- There must be good cooperation between academia, material suppliers, equipment suppliers, product producers, regulatory bodies, and recyclers and associations. If such cooperation does not exist, there will be little progress in this area.
- Regulations and purchasing guidelines specifying that new equipment contain no reused or refurbished parts need to be changed. If there is no motivation for buying products with recycled content, then there is no reason to develop the field of material science for reused materials.

Two recommendations address the key materials issues in an effective program:

- A coordinated research program on the properties of materials for reuse should be instituted. This research program could be a consortium, composed of major material suppliers, major material users, universities, recyclers and associations, or it could be a part of the new mission of the National Laboratories.
- A coordinated effort is needed to educate and convince consumers to buy products containing recycled material.

The biggest remaining question is whether customers will accept products with recycled contents. Frequently recycled material can affect the appearance of a product and it is not known whether a customer would be willing to forego a better-looking product made of virgin material in favor of one made of recycled material that performs the same function, yet may not have the same appearance as the product made of virgin material.

New Design Technologies

The handling of scrap electronic equipment to encourage recycling and materials recovery can be enhanced by incorporating or introducing features into new designs that facilitate material identification, segregation, toxic content, and disassembly. Designers traditionally select materials and design products based on factors such as proprietary designs, raw material price and availability, customer needs, and assembly time. This freedom of material selection and design latitude provides the consumer with a wide variety of products from which to choose--based on color, materials durability, aesthetic appeal, size, personal preference, cost, and optional features. However, the wide variety of materials, components, and assembly techniques required to allow this freedom, along with the need to handle and process each material separately, reduces recyclability and increases operation costs. To reduce this variability and enhance recyclability, designers may consider incorporating features and materials selection that will facilitate end-of-life disposition.

Some of the key issues to consider when developing new design technologies are:

- Attachment Technologies: To facilitate disassembly by recyclers, designers may consider the use of "snap fit" features in lieu of self-tapping, machine, and/or sheet metal fasteners. Where fasteners are necessary, designers may consider standardizing on one type of fastener head, such as a Phillips head, to avoid the need for a disassembler to constantly change tools. Permanent attachment methods (i.e., epoxies, welds, and hot staking) should be designed out of the assemblies.
- Marking for Ease of Identification: Disassemblers encounter a wide variety of materials, some of which are difficult to identify for proper segregation. Designers may consider marking various components to facilitate this identification. Plastics may have the international materials identification abbreviations and chasing arrows molded into the part; wire and cable may be marked to differentiate thermoplastics from thermosets; components may be marked to identify metallic content, (such as copper in coils and precious metals in mounted components); and printed circuit boards may be marked to indicate the use of lead based solders.
- Aesthetic Quality Technology: Customers demand aesthetic perfection on visible surfaces. This cosmetic requirement seriously inhibits the use of post-consumer materials. However, designers may consider specifying post-consumer recyclable materials for any non-visible parts. Designers may also consider changing surface texture requirements to hide surface imperfections resulting from the use of post-consumer materials.
- Material Properties/Characteristics: The physical, chemical, mechanical, and performance requirements of the materials often demand virgin raw materials. Efforts should be made to add post-consumer recyclable materials in concentrations that do not compromise the material and product integrity and functionality.

Potential deterrents to the development of new design technologies are:

- Consumers may reject products with imperfect surface features.
- Customer and regulatory agency requirements for materials may demand characteristics that can be obtained only by the use of virgin raw materials.
- Manufacturers may not be receptive to revealing the material identity of components, housings, subassemblies, etc.
- Attachment alternatives may involve time-consuming and expensive pre-production testing to evaluate the efficacy of alternative mechanisms.
- Designers may be reluctant to accept attachment methods that differ from individually preferred techniques and may resist criteria that inhibit their individual creativity.

Recommendations for the adoption of new design technologies are:

- A list of materials used for the manufacture of electronic equipment should be developed. This can be accomplished by electronic equipment representatives to trade associations.
- Manufacturers should agree upon a program to convince consumers that purchasing products manufactured with post-consumer materials may result in surface imperfections without sacrificing quality and/or functionality.
- Specification requirements should be reviewed to determine the extent to which chemical, physical, electrical, and/or mechanical properties can be changed to accommodate post-consumer materials without sacrificing quality.
- Electronic equipment and product manufacturers should meet within trade associations to develop standards for an acceptable universal identification program.
- Designers should be rewarded for innovative technical substitutions for use in lieu of traditional fastener systems.
- Industry standards and manufacturing specifications should be reviewed to identify requirements that inhibit reuse.

Market Pull

Electronic equipment disposition has the potential to encourage the development of several innovative market opportunities and enhance traditional markets already in place. In reality, this "market pull" (development) for the disposition of electronic equipment is a critical factor in the electronics industry environmental roadmap. Opportunities to provide value from electronic products and subsequent market development include:

- Performance-sensitive (early) reuse: Sell or lease used electronic equipment while its technology is relatively current.
- Price-sensitive (later) reuse: Sell or lease electronic equipment with adequate, but not cutting-edge, technology at attractive pricing.
- Service and support: Source or replacement parts for warranties and service as well as discontinued equipment.
- Component reuse: Use of component parts in new or refurbished equipment either by equipment manufacturer or third party.
- Residual material recovery and recycle.

To facilitate the market development for electronic equipment, the following major areas need to be addressed:

- Manufacturers of electronic equipment must begin to integrate product reuse opportunities into the business' strategic plan.
- Manufacturers of electronic equipment must begin to integrate product life cycle management (PLCM)/DFE into the product design.
- An infrastructure for collecting and returning equipment must be developed.
- Association of quality with reused equipment, parts and materials by both the electronic equipment manufacturer, third party purchasers for resale/reuse, and the customer must be more firmly established.
- Entrepreneurs must be recruited to invest and develop innovative electronics disposition markets globally.

Potential deterrents to the facilitation of market development for electronic equipment are:

- The inability for electronic equipment manufacturers to align their strategic business plan with potential reuse/resale opportunities and PLDM/DFE platforms.
- The inability of the manufacturer and customer to demonstrate that used equipment, parts, and materials are not of acceptable quality standards.

Key recommendations for accelerating market pull include:

- Provide high-level consumer awareness programs to encourage the reuse of used electronic equipment, parts, and materials, with specific emphasis focused at overcoming perceptions relating to inferior quality.
- Incorporate requirements for used equipment, parts, and material content into both corporate and government procurement practices and strategies, which in turn will effect strategic business planning and potentially lessen regulatory control initiatives.

Priority Needs Matrix

Priority Need (decreasing order of priority)	Approach	Selected Tasks
* Create design guidelines to enhance electronic product recyclability.	* Provide designers with a list of materials that are easier to reuse/recycle. * Promote cooperation between equipment manufacturers, suppliers and recyclers.	* Implement research on the properties of materials for reuse and recycle. * Establish a feedback loop between recyclers, suppliers, and OEM designers to affirm design decisions. * Encourage CAD/CAM

		suppliers to incorporate DFE/DFD in their programs.
* Assemble and disseminate information on disposition options.	* Develop information networks and sources to facilitate disposition decisions. * Establish analytical approaches for making disposition decisions.	* Create and populate databases to enhance disposition decisions. * Develop decision tools to aid the disposition process.
* Establish product disposition strategies and capabilities.	* Define an efficient electronics product disposition system. * Institute a mechanism for disseminating information on product content. * Assess costs/benefits of disposition options.	* Examine the success/failure of existing disposition approaches. * Develop a model electronics disposition system, leveraging off of existing systems.
* Improve product recycling strategies and capabilities.	* Establish collaboration strategies in conjunction with suppliers to enhance recycling efforts. * Examine technology needs at various recycling stages (e.g., separating, grinding).	* Develop low-cost part tracking technology. * Develop parts reliability database. * Establish technologies to sort electronic components. * Encourage government to offer financial incentives for start-up recycling operations.
* Develop markets for recycled products.	* Establish corporate and government procurement policies that encourage reuse and recycling. * Enhance markets for recycled products. * Expand the market for recycled plastics.	* Define requirements for recycled-product content. * Promote R&D to find new uses for recycled plastics. * Incorporate requirements for used equipment, parts and materials into procurements.
* Educate consumers about benefits of products containing recycled materials and/or reused components.	* Establish a coordinated, multi-industry effort to educate and convince consumers to accept recycled/reused products. * Reward suppliers and manufacturers publicly for innovative technical approaches to enhance recycling and recyclability.	* Institute programs to educate consumers on products containing recycled materials. * Develop global education programs on the costs/benefits of recycling and reuse issues.